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THESIS

FLOW GENERATION IN A NOVEL
CENTRIFUGAL DIFFUSER TEST DEVICE

by

Panagiotis Vidos

September 1983

Thesis Advisor: R. Shreeve

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Centrifugal Diffuser Test Device

by

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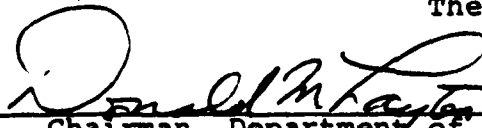
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ABSTRACT

Recognition of the need to develop optimum diffusers for advanced centrifugal compressors, resulted in the design and manufacture of a novel low-speed test facility for centrifugal diffuser testing. The CDTD was designed to allow the flow angle and wall boundary profiles into the test diffuser to be controlled by variable geometry in the flow generator. The present study reports on the design of the flow generator and the analysis of the internal flow using a NASA computer code (MERIDL). First test results are given and are compared with the results of a control volume analysis. The flow angle control technique was found to work effectively but to give somewhat smaller angles (by 4°) than were predicted. It was concluded that the information obtained would allow scaling of the device; however, an analysis code was needed which would accept the real physical boundary conditions.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Cross sectional area for hydraulic diameter calculation
A_{JW}	Total outflow area of one jet-wall (A_{JW} = .059 FT^2)
A_{SV}	Outflow cross sectional area of one SV (A_{SV} = .000436 FT^2)
A_{T1}	Total flow area out of the GC
A_{T2}	Total flow area out of the diffuser
A_{MIX}	Total mixing area per swirl vane
A_i	Area at station (i)
CDTD	Centrifugal diffuser test device
C	Wetted perimeter for hydraulic diameter calculation
C_F	Friction coefficient
C_P	Pressure term (sudden expansion)
C_τ	Friction term
d_h	Hydraulic diameter
$\vec{F}$	Force
GC	Generating cylinder
IW	Total surface area of the inner walls of the CDTD
JW	Jet walls
K_{b1}	Blockage factor at the outlet of the swirl vanes
K_{b2}	Blockage factor at the inlet of the test section
ℓ	Spanwise length (variable of integration)
L_1	Half exposed length of the generating cylinder ($2L_1 = \ell_1$)
ℓ_1	Exposed length of the generating cylinder (total jet-wall spacing)

L_2 Half span of the test section ($2L_2 = \ell_2$)

L_2^* Initially designed half span of the test section ($2L_2^* = \ell_2^*$)

ℓ_2 Span of the test section

ℓ_2^* Initially designed span of the test section

$\overset{\circ}{m}_i$ Mass flow rate

M_{aw} Moment exerted on the wall surfaces by the air about the longitudinal axis of the CDTD

N Number of corrugations per exposed length of the generating cylinder ($N = 19.104 \ FT^{-1}$)

$\hat{n}$ Outward normal unit vector

OC Outer casing of the CDTD

P_{KIEL} Kiel probe

P_{5H} Five hole probe

$P_{S_{GC}}$ Static pressure at the surface of the generating cylinder

$P_{S_{OC}}$ Static pressure at the surface of the outer casing

P_{t1} Stagnation pressure at the outlet of the swirl vanes

P_{t1}' Stagnation pressure after jet mixing

p_w Normal stress on the non cylindrical surfaces of the swirl vanes

P_1 Static pressure at the outlet of a swirl vane

$\bar{R}$ Mean radius of the generating cylinder location ($\bar{R} = 19.1 \ IN$)

R_H Radius at the hub of the flow model

R_h Hydraulic radius

R_S Radius at the shroud of the flow model

Re Reynolds number

R_1 Radius at the surface of the generating cylinder

R_2 Radius at the test section inlet

SV	Swirl vanes
TS	Test section
$\hat{t}$	Tangential unit vector
V_z	Axial velocity (at the z direction)
V_{R_i}	Radial velocity component at station (i)
V_i	Total velocity at station (i)
$\bar{V}_{IW}$	Average velocity for the flow over the inner walls of the CDTD
$\bar{V}_{ij}$	Area average velocity
$\bar{\bar{V}}_{ij}$	Mass average velocity
$V_{\theta i}$	Tangential velocity component at station (i)
$\bar{V}_1$	Average velocity out of the swirl vanes
z	Number of corrugations per revolution of the generating cylinder
z	Longitudinal (axial) direction
β_i	Flow angle at station (i)
$\bar{\bar{\beta}}_2$	Mass average flow angle at the test section
ν	Kinematic viscosity
ρ_i	Density at station (i)
ψ	Stream function

ACKNOWLEDGMENTS

I. INTRODUCTION

Centrifugal compressors are currently used in gas turbine power units for turboprop aircraft, helicopters and auxiliary power production. The capability of achieving high pressure ratios per stage (12:1), and the simplicity of design & fabrication, are reasons for using centrifugal rather than axial stages in smaller engine types. The main disadvantage is the progressively lower efficiencies obtained as the pressure ratio is increased.

A major contributor to centrifugal compressor inefficiency is the performance of the diffuser which closely follows the impeller of the compressor. The purpose of the centrifugal diffuser is to convert most of the kinetic energy of the flow entering the diffuser vanes into static pressure, with the highest efficiency attainable.

The design of centrifugal diffusers is presently based mainly on experimental results for two dimensional and conical diffusers. While numerical methods are currently under development, computer solutions to viscous, three dimensional, unsteady, transonic flows, with adverse static pressure gradients are not yet available as verified tools to be used to optimize designs.

Centrifugal diffusers are currently tested only as components of high speed compressors or gas turbine engines.

This approach is very expensive and does not yield detailed, accurate information which is necessary to confirm design systems or to provide the basis for improved theoretical analysis.

A new test facility [Ref. 1] has been proposed and built, the so-called CDTD (Centrifugal Diffuser Test Device), which has as its main purpose the large scale, controlled simulation of the time-averaged inlet flow to centrifugal compressor diffusers. The device will allow the detailed evaluation of proposed diffuser geometries at an acceptable expense, and will permit validation of new computer analysis codes for diffusers operating in a fully subsonic flow regime.

This report deals only with the flow generation within the CDTD, the control of which was to be effected in a novel way. The flow was supplied through a central, swirl generating cylinder (GC) and the average angle of the flow into the diffuser under test, was to be controlled by covering or exposing more or less of the cylinder's length.

The design and the calculations on which the device was based, are given in Chapter II. In the same section are also described the results obtained of modeling the flow-field generation using the NASA computer code MERIDL [Ref. 2]. In order to use the code, in its standard form, artificial boundary conditions were used to obtain nearly representative conditions at the physical boundaries.

Selected results from the initial program of measurements, carried out on the CDTD, operating in effect without a diffuser, are given in Chapter III.

The flow angle control principle, was shown to work qualitatively, however the angle produced for a given exposed length of the central cylinder, were found to be less (by 5°-10°) than were predicted in the design calculations.

Reasons for the observed differences between design and test results are discussed in Chapter IV. It is shown (Appendix D) that a control-volume analysis of the flow generation, in which the geometry of the swirl generating cylinder surface, mixing and wall effects are included, can be used to predict the measured results.

It is concluded in Chapter V that by using the results of measurements to establish reasonable values for unknown factors in the control-volume analysis, a means of scaling the design is obtained.

Finally, it is recommended that an axi-symmetric, inviscid analysis of the flow generation, in which the physical boundary conditions are more properly represented, be carried out.

II. CDTD DESIGN

A. DESCRIPTION

The Centrifugal Diffuser Test Device (CDTD), is located in the Cascade Building (213) at the Turbopropulsion Laboratory complex of the Naval Postgraduate School. A view of the apparatus is shown in Fig. 1. A schematic is shown in Fig. 2.

The philosophy in the design of the CDTD was to provide a nearly tangentially-directed, uniform airflow from a large cylinder, have a minimum decrease in tangential velocity between the cylinder and the test diffuser (conserving angular momentum) while the exposed length of the cylinder would control the radial component of velocity and hence the average flow angle (β_2) entering the test diffuser.

The device consists of the following major components with their corresponding functions.

1. Perforated Cylinder (Fig. 2, Index 5)

The perforated cylinder serves as a major structural component of the CDTD, holds the north and south plates in parallel and concentric alignment and provides uniformly distributed air at low velocity around its periphery.

2. Generating Cylinder (Fig. 2, Index 10)

The generating cylinder is placed around the perforated cylinder and consists of the following components.

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a. Central Section (Fig. 2, Index 12)

The central section is made of sets of small nozzles (not 2-D vanes as shown in the schematic) formed by pressing & bending sheet metal strips and soldering them to form a drum. A view of the complete section is shown in Fig. 3. The nozzles provide an almost tangential velocity which is controlled by the pressure supplied at the inlet.

b. North & South End Cylinders (Fig. 2, Index 11)

These support the central section. They each contain a short length of porous section inside of which cylindrical throttles (Fig. 2, Index 6) are arranged to slide. The throttles, operating separately, expose or cover the porous sections, so controlling the air supplied to the jet walls.

3. Jet Walls (Fig. 2, Index 3)

These are annular end walls containing nozzles distributed radially, so that nearly tangential injection is produced through them (the same nozzles as for the generating cylinder are used). By-pass air, depending on the throttle positioning is routed through the jet walls, to effect changes in the velocity distribution at the diffuser inlet. The jet walls are also the means for controlling the main airflow into the test section (TS). The mass flow through the swirl vanes, is controlled by moving the jet walls axially, and so exposing more or less of the swirl vane area. Thus the velocity profile and the average flow

angle (β_2) at the test section, are controlled by the jet walls and associated throttle positions.

4. Other Components

The outer casing (Fig. 2, Index 9) contains a contraction contour (Fig. 2, Index 8), which is designed to turn the flow into a radial, parallel-wall test section containing the diffuser vanes under test.

B. DESIGN CALCULATIONS

The CDTD design calculations are presented in Appendix A. The concepts of continuity and conservation of angular momentum were applied to an incompressible, inviscid flow. The detailed geometry of the inlet surface and effects of friction were not considered.

Selected flow angles (β_2) and jet wall spacings (L_2), were input into the derived formulae, and the results are given in Table A1 and Figure 29.

C. FLOW ANALYSIS

A FORTRAN computer program MERIDL [Ref. 2] was used to obtain a prediction of the flowfield generated by the CDTD.

Specifically, in the design phase the main interest was to investigate the velocity behavior along the contraction contour (Fig. 2, Index 8), in order to verify that the flow is turned without adverse deceleration ahead of the test vanes, into the diffuser.

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MERIDL, besides its general applications for calculating flows through blade rows in turbomachines, can obtain solutions for flow in annular ducts without blades.

The flow must be essentially subsonic and the solution obtained is for two-dimensional axi-symmetric, compressible, shock free flow. Upstream and downstream flow conditions can vary from hub to shroud, and provision is made for an appropriate correction for loss of stagnation pressure.

The analysis consists of the solution of the simultaneous, non-linear, finite-difference equations for the stream function (ψ).

The following assumptions are made:

(1) The fluid is a perfect gas with constant specific heat C_p.

(2) The only forces along a hub-shroud orthogonal mesh line are those due to momentum and pressure gradient (viscous forces are neglected in that direction).

(3) There is no heat transfer.

(4) The upstream and downstream boundaries of the solution region are orthogonal to the streamlines.

(5) The stream function is zero at the hub and 1.0 at the shroud.

The program generates an orthogonal mesh in the space between the hub and the shroud, by dividing it into equal increments along several hub-shroud lines. Spline curves are fit through the resulting points to obtain the streamwise

orthogonals. The normal orthogonals are obtained by a predictor-corrector technique. The solution of the equations follows an iterative method with successive overrelaxation.

1. Flowfield Modelling

An equivalent flowfield to the one generated by the CDTD had to be formulated in order to overcome MERIDL's inability to accommodate the real physical boundary condition along the generating cylinder.

The author of Reference 2 was consulted and the geometric model shown in Fig. 4 was developed after appropriate calculations were carried out (Appendix B).

The inflow stream was introduced with a constant whirl ($R_\theta r$ = const.) far upstream of the TS. The channel height was doubled so that the streamlines, close to the region of the contraction contour, approximated the actual flow pattern generated by the device .

The input files to MERIDL (Appendix E) were generated and the program was run using the Naval Postgraduate School's IBM 370-3033 computer.

2. Results

Selected tabulated results (for ψ = 0.0 and ψ = 1.0) from the converged output files generated by MERIDL are given in Appendix F.

The TEKTRONIX 618 plotter was used to plot the streamlines of the computed flowfield (Fig. 5a). An enlargement of the area of main interest around the contraction contour is shown in Fig. 5b.

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The relative velocity along the outer casing wall ($\psi = 1.0$), for the selected runs, is shown plotted in Fig. 6. The flow appears to be accelerating in the region of the contraction contour (stations 14-23) and then begins to diffuse.

Finally in Figures 7 and 8 the velocity and the flow angle variations are shown plotted for the $\psi = 0.0$ streamline from the surface of the GC ($R_1 = 1.5833$ FT) up to the TS inlet ($R_2 = 2.1$ FT). The velocity is seen to diffuse smoothly and the flow angle decreases to almost a constant value at the inlet station to the test vanes.

A check was made of the velocity and flow angle uniformity at the location of the GC. The results are given in Table 1. Values between stations were obtained by linear interpolation of the tabulated output from MERIDL. The results show that the conditions expected, at the surface of uniform velocity and angle, appear to have been achieved with a maximum deviation of .5% in the velocity and 2.4% in the flow angle (β_1) at outlet flow angles from 60° to 75°.

Comparisons of the predictions with measurements will be made when pressure taps have been installed along the outer casing and the contraction contour, as discussed in subsection III.A.2.

III. PRELIMINARY TEST PROGRAM

Preliminary measurements were carried out as shown in
Figure 9, using a short vaneless diffuser, obtained by re-
placing the plexiglass walls (Fig. 2, Index 13), with locally
fabricated plywood walls (Fig. 9, Index 4). The walls ended
at the intended location of the leading edge of the test
vanes.

The data were taken using two pressure probes, one United
Sensor 5-hole and one Kiel probe. Both probes were connected
to a manometer board, inclined at a 30° angle for greater
sensitivity.

A. INSTRUMENTATION

1. Installed for Preliminary Measurements

The instrumentation arrangement is indicated in
Figure 9. The 5-hole probe (Fig. 9, Index 1) was attached
to the south half of the outer casing which could rotate to
facilitate circumferential measurements. The radial position
of the probe corresponded to the leading edge of the test
vanes (R_2 = 25"). The probe could traverse axially in order
to obtain data for the total pressure and flow angle dis-
tributions, as well as for the velocity profile, produced
across the outlet from the plywood walls (parallel to the
main axis of the device).

The Kiel probe (Fig. 9, Index 5) was moved radially from the GC surface (R_I = 19"), up to the intended location of the LE of the test vanes (R_2 = 25"), and axially (from wall to wall). The purpose of measurements inside the flow generator was specifically to obtain:

a. The flow mixing pattern out of the swirl vanes and from the GC up to the outer casing.

b. Wake visualization close to the surface of the GC.

c. The blockage factor (K_{B_1}) for the flow, at the exit of the nozzles.

2. <u>Not Installed for Preliminary Measurements</u>

A set of pressure taps was designed to be drilled on the contraction contour and on the outer casing, as shown in Figures 10a and 10b in order to obtain data to compare with the results generated using MERIDL.

The proposed arrangement is shown in Fig. 10a, drawn on the north (fixed) part of the apparatus. The circumferential tap distribution is indicated in Fig. 10b, for both rotating and fixed walls.

A tap size of .04 inches diameter (.001 m) was selected. Pressure data can be recorded using the laboratory's HP 3052 Data Acquisition System with Scanivalve interface.

B. PROGRAM OF MEASUREMENTS

The goals of the preliminary measurements were:

a. To verify the effectiveness of the flow control method,

b. To visualize the flowfield,

c. To verify circumferential symmetry,

d. To measure the total pressure and flow angle (β_2) distributions at the inlet to the test section.

A series of tests were conducted, at a plywood wall spacing of 2.62" (varying slightly circumferentially), at selected jet wall spacings and throttle settings. Probe measurements were also taken at various circumferential positions.

C. RESULTS

Data from selected runs are presented in Tables 2 through 17.

The data obtained from the measurements were reduced using the methods of averaging derived in Appendix C. The averages were obtained assuming incompressible flow and using the equations for conservation of mass and angular momentum.

A computer program was developed, to carry out the required calculations. Spanwise (gapwise) integrations were accomplished using the subroutine DATINT from Reference 3.

From the computations, blockage factors (K_{b_2}), and mass averaged flow angles ($\bar{\bar{\beta}}_2$) were obtained at the inlet of the test section for various configurations of the apparatus.

IV. <u>DISCUSSION</u>

A. EXPERIMENTAL RESULTS

The initial results showed that:

1. The flow control method was working, but the flow angle was not affected as much as was expected by jet wall spacing changes.

2. The measured maximum average flow angle β_2 was less than the design angle of 70°.

3. The flowfield generated by the device was qualitatively as expected and mixing of the jets from the swirl vanes occurred very quickly.

4. Circumferential symmetry of the measured flow angle β_2 at the exit of the plywood walls was not achieved.

In trying to explain the results, the importance of the leak which was forced to occur at the interface of the GC surface and the jet walls, in all but the maximum ($\ell_1 = 24.375"$), spacings was examined. Table 2-9 gives data for $\ell_1 = 24.375"$.

A survey with a tuft at minimum jet wall spacing ($\ell_1 = 7.0"$) showed that significant axial component of velocity and a vortex flow were generated at the gap, as shown in Figure IV.1 below.

A vortical recirculation region was established near the jet wall, between the outer casing (higher static pressure region) and the generating cylinder surface (lower
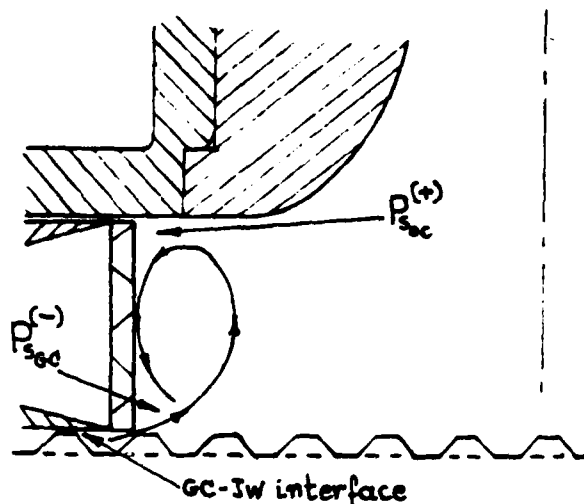
Figure IV.1. Schematic of the Vortex Flow Generated
at the GC-JW Interface

static pressure region), which would contribute to a reduc-

tion in the total pressure and flow angle along the contrac-

tion cone. In addition, non-uniformity in the leak

circumferentially, would result in non-uniformity in the

circumferential measurements.

Sealing of the gap, using strips of upholstery piping,

resulted in the data given in Tables 1-17. Noted were:

1. An increase in flow angle β_2 by approximately 4°

(Figs. 11 and 12) and improvement in the total pressure

distribution (Figs. 13 and 14).

2. Satisfactory circumferential uniformity in flow angle

(Figs. 15 and 16) and total pressure (Figs. 17 and 18).

3. The effect of the jet wall spacing on β_2 (Fig. 19) approached more closely the design expectation (Fig. 29), the difference which remained will be discussed in the following subsection.

In Fig. 20 is shown the effect of JW spacing on the total pressure distribution at the location where the measurements were taken.

Figures 21 through 24 show the effect of the JW throttle setting on the flow angle (Figs. 21 and 22) and on the total pressure (Figs. 23 and 24), for the two JW spacings at which reliable (leak-free) measurements were taken

Figures 25 through 28 show circumferential measurements of the flow angle and the total pressure distributions for the jet walls in the fully retracted position.

B. THEORY AND EXPERIMENT

In Fig. 29 are shown the results for the measured flow angle (averaged as described in Appendix C) and the values obtained in Appendix A, using the design calculation method, for the wall spacing at the time of the tests of 2.62". The experimental values are seen to be lower by 4° at maximum and 8° at minimum jet wall spacing.

The design calculation was based on an idealized flow-field and was immediately questioned. A complete control volume analysis (Appendix D) was carried out in order to take into account the geometry of the generating cylinder and the contributions of wall friction.

Examples of results are plotted in Fig. 29. The control volume analysis appears to agree well with the measured values when the JW's are widely spaced, but to predict a stronger effect of reducing the spacing than is actually measured. The significant differences between the idealized design predictions and the control volume analysis however, imply that the geometry of the generating cylinder surface and effects of friction need to be included in analyzing the flow. It is noted that the control volume analysis includes one unknown blockage factor, and one which must be input from measurements. Further examination needs to be made of the uncertainties in the analysis, in order to explain the differences in the slopes of the lines in Fig. 29.

Finally in Fig. 29 are shown the calculated flow angles corresponding to the design value of the diffuser wall spacing (2.0"). Clearly an increase of the wall spacing results in an increase of the flow angle. Any desired range of flow angle can be obtained by changing the width (or span) of the test diffuser.

V. CONCLUSIONS

From the work reported, the following conclusions were drawn:

1. The proposed method of flow control works satisfactorily.

2. Sealing the jet wall gap is essential, in order to obtain the desired flow angles and circumferential flow symmetry. A method to provide sealing, at specific values of jet wall spacing must be designed in order to achieve the desired working range of diffuser inlet flow angle.

3. A review of the control volume analysis is necessary in order to explain the measured flow angles.

4. While results obtained with MERIDL were not unrealistic, the development of a computer code which will accept the proper boundary conditions, for the CDTD, is needed in order to predict more accurately the distributions of flow conditions at the test section inlet.

An advanced code with transonic flow capability is required ultimately for the design of a high speed version of the CDTD.

TABLE 1

FLOW CONDITIONS CALCULATED AT THE SURFACE OF THE GENERATING CYLINDER FOR MERIDL MODEL CHCK

β_1 SL	60°		65°		70°		75°	
	V_1	β_1	V_1	β_1	V_1	β_1	V_1	β_2
.00	220.17	83.41	229.86	84.71	237.92	85.92	244.26	87.06
.05	220.46	83.01	230.11	84.35	238.14	85.59	244.45	86.75
.1	220.69	82.59	230.28	83.99	238.14	85.27	244.57	86.48
.15	220.87	82.21	230.41	83.67	238.34	85.02	244.53	86.27
.20	221.08	88.81	230.54	83.34	238.37	84.78	244.24	86.09
.25	221.39	81.26	230.75	82.90	238.56	84.44	244.69	85.85
.30	221.78	80.64	231.02	82.40	238.72	84.06	244.80	85.59
.35	222.14	80.07	231.27	81.95	238.12	83.71	244.87	85.34
.40	222.44	79.60	231.53	81.57	239.18	83.41	244.94	85.11

UNITS

In Tables 1-17, velocity [V] is in ft/sec, angle [β] is in degrees, displacement (L2) is in inches and the reading of the inclined manometer (DP) showing the difference between impact and atmospheric pressure--is in inches of water.

TABLE 2 (WEST)

JW SPACING: 24.375 IN
THROTTLES: "OPEN"

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTI28	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDTI28	.15	7.05	58.20	115.15	60.68	97.86	80.86
CDTI28	.35	10.55	54.60	140.86	81.60	114.82	127.57
CDTI28	.75	12.15	55.60	151.16	85.40	124.73	145.04
CDTI28	1.25	11.85	56.80	149.29	81.74	124.92	139.04
CDTI28	1.75	11.80	57.40	148.97	80.26	125.50	137.16
CDTD28	2.15	11.05	58.20	144.16	75.97	122.52	126.73
CDTD28	2.35	8.65	60.40	127.55	63.00	110.90	95.14
CDTD28	2.62	0.00	0.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY 134.82
AREA AVERAGED RADIAL VELOCITY 73.44
MASS AVERAGED RADIAL VELOCITY 78.84
MASS AVERAGED TANGENTIAL VELOCITY 120.77
BLOCKAGE FACTOR .93
AVERAGED FLOW ANGLE 56.86

TABLE 3 (BOTTOM)

JW SPACING: 24.375 IN
THROTTLES: "OPEN"

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTI29	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDTD29	.15	6.65	60.80	111.83	54.56	97.62	72.91
CDTD29	.35	9.70	57.20	135.07	73.17	113.53	113.71
CDTD29	.75	11.55	56.00	147.38	82.42	122.19	137.85
CDTD29	1.25	11.30	56.20	145.78	81.10	121.14	134.48
CDTD29	1.75	11.50	56.00	147.06	82.24	121.92	137.26
CDTD29	2.15	10.55	55.00	140.86	80.79	115.39	127.62
CDTD29	2.35	8.55	56.00	126.81	70.91	105.13	102.05
CDTD29	2.62	0.00	0.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY 131.79
AREA AVERAGED RADIAL VELOCITY 73.05
MASS AVERAGED RADIAL VELOCITY 78.37
MASS AVERAGED TANGENTIAL VELOCITY 117.24
BLOCKAGE FACTOR .93
AVERAGED FLOW ANGLE 56.24

TABLE 4 (EAST)

JW SPACING: 24.375 IN
THROTTLES: "OPEN"

RUN	L2	DP	BETA	V	VF	VT	VTM
CDTD30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDTD30	.15	5.40	68.40	100.78	37.10	93.70	51.02
CDTD30	.35	9.10	60.60	130.82	64.22	113.97	107.44
CDTD30	.75	11.40	59.00	146.42	75.41	125.51	138.93
CDTD30	1.25	11.40	59.80	146.42	73.65	126.55	136.82
CDTD30	1.75	11.88	57.80	149.47	79.65	126.48	147.88
CDTD30	2.15	11.50	56.40	147.06	81.38	122.49	146.33
CDTD30	2.35	9.80	56.80	135.76	74.34	113.60	123.95
CDTD30	2.62	0.00	0.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   132.53
AREA AVERAGED RADIAL VELOCITY   68.13
MASS AVERAGED RADIAL VELOCITY   74.00
MASS AVERAGED TANGENTIAL VELOCITY 121.85
BLOCKAGE FACTOR   .92
AVERAGED FLOW ANGLE   58.73

TABLE 5 (TOP)

JW SPACING: 24.375 IN
THROTTLES: "OPEN"

RUN	L2	DP	BETA	V	VF	VT	VTM
CDTD31	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDTD31	.15	6.70	62.40	112.25	52.01	99.48	78.00
CDTD31	.35	10.05	58.00	137.48	72.85	116.59	128.06
CDTD31	.75	11.60	57.40	147.70	79.58	124.43	149.29
CDTD31	1.25	11.10	58.00	144.48	76.56	122.53	141.44
CDTD31	1.75	11.00	58.60	143.83	74.94	122.77	138.71
CDTD31	2.15	9.20	60.00	131.54	65.77	113.92	112.96
CDTD31	2.35	6.85	64.60	113.50	48.69	102.53	75.26
CDTD31	2.62	0.00	0.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   129.00
AREA AVERAGED RADIAL VELOCITY   66.33
MASS AVERAGED RADIAL VELOCITY   71.97
MASS AVERAGED TANGENTIAL VELOCITY 118.66
BLOCKAGE FACTOR   .92
AVERAGED FLOW ANGLE   59.76

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TABLE 6 (WEST)

JW SPACING: 24.375 IN
THROTTLES: CLOSED

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD37	0.00	0.00	90.00	0.00	0.00	0.00	0.00
CDTD37	.15	6.70	66.40	112.25	44.94	102.86	67.20
CDTD37	.35	10.50	60.00	140.53	70.26	121.70	124.29
CDTD37	.75	12.80	58.00	155.15	82.22	131.58	157.25
CDTD37	1.25	12.55	59.00	153.63	79.13	131.69	151.46
CDTD37	1.75	12.60	59.20	153.94	78.82	132.23	151.50
CDTD37	2.15	11.30	60.40	145.78	72.01	126.76	132.67
CDTD37	2.35	9.20	64.00	131.54	57.66	118.23	99.09
CDTD37	2.62	0.00	90.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   137.60
AREA AVERAGED RADIAL VELOCITY   68.80
MASS AVERAGED RADIAL VELOCITY   74.62
MASS AVERAGED TANGENTIAL VELOCITY 127.68
BLOCKAGE FACTOR   .92
AVERAGED FLOW ANGLE   59.70

TABLE 7 (TOP)

JW SPACING: 24.375 IN
THROTTLES: CLOSED

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTI38	0.00	0.00	90.00	0.00	0.00	0.00	0.00
CDTI38	.15	7.15	66.00	115.96	47.17	105.94	69.48
CDTI38	.35	11.15	60.00	144.81	72.40	125.41	126.26
CDTI38	.75	13.60	58.70	159.93	83.09	136.65	157.88
CDTI38	1.25	13.10	59.00	156.96	80.84	134.54	151.24
CDTD38	1.75	13.30	59.00	158.16	81.46	135.57	153.55
CDTI38	2.15	12.65	59.40	154.24	78.52	132.76	144.95
ČDTD38	2.35	10.70	61.20	141.86	68.34	124.31	119.13
CDTD38	2.62	0.00	90.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   142.54
AREA AVERAGED RADIAL VELOCITY   71.92
MASS AVERAGED RADIAL VELOCITY   77.56
MASS AVERAGED TANGENTIAL VELOCITY 131.72
BLOCKAGE FACTOR   .93
AVERAGED FLOW ANGLE   59.51

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TABLE 8 (BOTTOM)

JW SPACING: 24.375 IN
THROTTLES: CLOSED

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD39	0.00	0.00	90.00	0.00	0.00	0.00	0.00
CDTD39	.15	8.70	62.00	127.91	60.05	112.94	87.24
CDTD39	.35	12.50	57.40	153.33	82.61	129.17	137.24
CDTD39	.75	13.95	57.40	161.97	87.27	136.46	153.16
CDTD39	1.25	13.35	57.60	158.45	84.90	133.79	146.10
CDTD39	1.75	13.55	57.80	159.64	85.07	135.08	147.80
CDTD39	2.15	12.90	56.20	155.76	86.65	129.43	144.25
CDTD39	2.35	10.50	57.40	140.53	75.71	118.39	115.28
CDTD39	2.62	0.00	90.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY 145.27
AREA AVERAGED RADIAL VELOCITY 77.75
MASS AVERAGED RADIAL VELOCITY 83.23
MASS AVERAGED TANGENTIAL VELOCITY 130.94
BLOCKAGE FACTOR   .93
AVERAGED FLOW ANGLE   57.56

TABLE 9 (EAST)

JW SPACING: 24.375 IN
THROTTLES: CLOSED

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD40	0.00	0.00	90.00	0.00	0.00	0.00	0.00
CDTD40	.15	8.45	66.20	126.06	50.67	115.34	83.05
CDTD40	.35	11.80	61.00	148.97	72.22	130.29	133.18
CDTD40	.75	14.30	59.40	163.99	83.43	141.16	166.78
CDTD40	1.25	14.30	59.40	163.99	83.43	141.16	166.78
CDTD40	1.75	14.45	60.00	164.85	82.43	142.77	166.55
CDTD40	2.15	12.40	61.80	152.71	72.16	134.58	137.46
CDTD40	2.35	9.10	66.20	130.82	52.79	119.70	89.44
CDTD40	2.62	0.00	90.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY 145.70
AREA AVERAGED RADIAL VELOCITY 70.65
MASS AVERAGED RADIAL VELOCITY 76.96
MASS AVERAGED TANGENTIAL VELOCITY 126.66
BLOCKAGE FACTOR   .92
AVERAGED FLOW ANGLE   60.64

TABLE 10 (WEST)

JW SPACING: 8.0 IN
THROTTLES: CLOSED

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD81	0.00	0.00	90.00	0.00	0.00	0.00	0.00
CDTD81	.15	4.20	82.00	88.88	12.37	88.01	36.86
CDTD81	.35	4.90	80.80	96.00	15.35	94.76	49.25
CDTD81	.75	6.55	74.60	110.99	29.47	107.00	106.80
CDTD81	1.25	8.65	67.60	127.55	48.60	117.92	194.08
CDTD81	1.75	8.10	69.20	123.42	43.83	115.38	171.24
CDTD81	2.15	5.15	75.40	98.42	24.81	95.24	80.00
CDTD81	2.35	3.75	78.00	83.98	17.46	82.14	48.57
CDTD81	2.62	0.00	90.00	0.00	0.00	0.00	0.00

```
AREA AVERAGED OVERALL VELOCITY   102.59
AREA AVERAGED RADIAL VELOCITY     29.53
MASS AVERAGED RADIAL VELOCITY     36.93
MASS AVERAGED TANGENTIAL VELOCITY 108.91
BLOCKAGE FACTOR        .80
AVERAGED FLOW ANGLE    71.27
```

TABLE 11 (TOP)

JW SPACING: 8.0 IN
THROTTLES: CLOSED

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD82	0.00	0.00	90.00	0.00	0.00	0.00	0.00
CDTD82	.15	3.00	79.00	75.11	14.33	73.73	39.54
CDTD82	.35	3.95	77.00	86.19	19.39	83.98	60.92
CDTD82	.75	6.45	71.00	110.14	35.86	104.14	139.71
CDTD82	1.25	8.05	67.60	123.04	46.89	113.76	199.57
CDTD82	1.75	6.45	73.20	110.14	31.83	105.44	125.58
CDTD82	2.15	5.00	81.60	96.97	14.17	95.93	50.84
CDTD82	2.35	4.05	84.60	87.27	8.21	86.89	26.70
CDTD82	2.62	0.00	90.00	0.00	0.00	0.00	0.00

```
AREA AVERAGED OVERALL VELOCITY    97.34
AREA AVERAGED RADIAL VELOCITY     26.73
MASS AVERAGED RADIAL VELOCITY     34.54
MASS AVERAGED TANGENTIAL VELOCITY 103.93
BLOCKAGE FACTOR        .77
AVERAGED FLOW ANGLE    71.62
```

TABLE 12 (BOTTOM)

JW SPACING: 8.0 IN
THROTTLES: CLOSED

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTI83	0.00	0.00	90.00	0.00	0.00	0.00	0.00
CDTI83	.15	4.00	80.80	86.73	13.87	85.62	40.71
CDTD83	.35	4.80	79.40	95.01	19.10	93.07	60.97
CDTD83	.75	6.55	73.60	110.99	31.34	106.47	114.41
CDTD83	1.25	8.25	68.20	124.56	46.26	115.65	183.45
CDTD83	1.75	7.50	71.40	118.77	37.88	112.56	146.22
CDTD83	2.15	5.80	76.00	104.44	25.27	101.34	87.80
CDTI83	2.35	4.75	78.00	94.52	19.65	92.45	62.30
CDTD83	2.62	0.00	90.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   102.64
AREA AVERAGED RADIAL VELOCITY   29.16
MASS AVERAGED RADIAL VELOCITY   34.63
MASS AVERAGED TANGENTIAL VELOCITY 107.62
BLOCKAGE FACTOR   .84
AVERAGED FLOW ANGLE   72.16

TABLE 13 (EAST)

JW SPACING: 8.0 IN
THROTTLES: CLOSED

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD84	0.00	0.00	90.00	0.00	0.00	0.00	0.00
CDTI84	.15	4.10	82.00	87.81	12.22	86.96	38.03
CDTD84	.35	5.05	80.00	97.46	16.92	95.97	58.13
CDTI84	.75	7.10	73.60	115.55	32.63	110.85	129.44
CDTI84	1.25	8.65	68.40	127.55	46.95	118.59	199.28
CDTD84	1.75	6.95	70.60	114.33	37.98	107.84	146.56
CDTD84	2.15	4.35	77.20	90.45	20.04	88.20	63.25
CDTD84	2.35	3.50	80.80	81.13	12.97	80.09	37.18
CDTI84	2.62	0.00	90.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   100.74
AREA AVERAGED RADIAL VELOCITY   27.94
MASS AVERAGED RADIAL VELOCITY   35.03
MASS AVERAGED TANGENTIAL VELOCITY 107.74
BLOCKAGE FACTOR   .80
AVERAGED FLOW ANGLE   71.99

TABLE 14 (EAST)

JW SPACING: 8.0 IN
THROTTLES: OPEN

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD86	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDTD86	.15	4.40	81.80	90.97	12.97	90.04	32.01
CDTD86	.35	5.95	77.20	105.78	23.44	103.15	66.24
CDTD86	.75	9.80	70.00	135.76	46.43	127.57	162.30
CDTD86	1.25	11.40	67.40	146.42	56.27	135.18	208.42
CDTD86	1.75	10.00	69.00	137.14	49.15	128.03	172.40
CDTD86	2.15	5.85	74.50	104.89	28.03	101.08	77.63
CDTD86	2.35	5.20	78.80	98.89	19.21	97.01	51.06
CDTD86	2.62	0.00	0.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   116.57
AREA AVERAGED RADIAL VELOCITY   36.50
MASS AVERAGED RADIAL VELOCITY   44.56
MASS AVERAGED TANGENTIAL VELOCITY 123.43
BLOCKAGE FACTOR   .82
AVERAGED FLOW ANGLE   70.15

TABLE 15 (BOTTOM)

JW SAPCING: 8.0 IN
THROTTLES: OPEN

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD87	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDTD87	.15	5.65	81.60	103.08	15.06	101.98	40.60
CDTD87	.35	7.05	78.00	115.15	23.94	112.63	71.29
CDTD87	.75	9.55	70.00	134.02	45.84	125.94	152.62
CDTD87	1.25	11.05	67.40	144.16	55.40	133.09	194.95
CDTD87	1.75	9.75	68.00	135.41	50.73	125.55	168.40
CDTD87	2.15	6.15	72.40	107.55	32.52	102.51	88.14
CDTD87	2.35	4.60	74.00	93.01	25.64	89.41	60.61
CDTD87	2.62	0.00	0.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   117.12
AREA AVERAGED RADIAL VELOCITY   37.82
MASS AVERAGED RADIAL VELOCITY   44.69
MASS AVERAGED TANGENTIAL VELOCITY 121.62
BLOCKAGE FACTOR   .85
AVERAGED FLOW ANGLE   69.32

TABLE 16 (WEST)

JW SPACING: 8.0 IN
THROTTLES: OPEN

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD88	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDTD88	.15	3.30	82.20	78.78	10.69	78.05	22.20
CDTD88	.35	4.95	78.00	96.49	20.06	94.38	50.36
CDTD88	.75	9.60	69.60	134.37	46.84	125.94	156.90
CDTD88	1.25	11.85	67.10	149.29	58.09	137.52	212.49
CDTD88	1.75	11.05	68.60	144.16	52.60	134.22	187.79
CDTD88	2.15	7.90	74.60	121.89	32.37	117.51	101.18
CDTD88	2.35	5.95	78.80	105.78	20.55	103.77	56.71
CDTD88	2.62	0.00	0.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   118.79
AREA AVERAGED RADIAL VELOCITY   37.60
MASS AVERAGED RADIAL VELOCITY   46.51
MASS AVERAGED TANGENTIAL VELOCITY 126.62
BLOCKAGE FACTOR   .81
AVERAGED FLOW ANGLE   69.93

TABLE 17 (TOP)

JW SPACING: 8.0 IN
THROTTLES: OPEN

RUN	L2	DP	BETA	V	VR	VT	VTM
CDTD89	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDTD89	.15	5.50	80.00	101.70	17.66	100.16	47.09
CDTD89	.35	7.10	76.00	115.55	27.96	112.12	83.44
CDTD89	.75	9.85	69.40	136.11	47.89	127.40	162.42
CDTD89	1.25	11.10	66.80	144.49	56.92	132.80	201.23
CDTD89	1.75	8.95	68.40	129.74	47.76	120.63	153.37
CDTD89	2.15	5.40	73.20	100.78	29.13	96.47	74.81
CDTD89	2.35	3.75	77.00	83.98	18.89	81.83	41.15
CDTD89	2.62	0.00	0.00	0.00	0.00	0.00	0.00

AREA AVERAGED OVERALL VELOCITY   114.37
AREA AVERAGED RADIAL VELOCITY   37.56
MASS AVERAGED RADIAL VELOCITY   44.82
MASS AVERAGED TANGENTIAL VELOCITY 120.41
BLOCKAGE FACTOR   .84
AVERAGED FLOW ANGLE   69.58

Figure 1. View of the CDTD

37
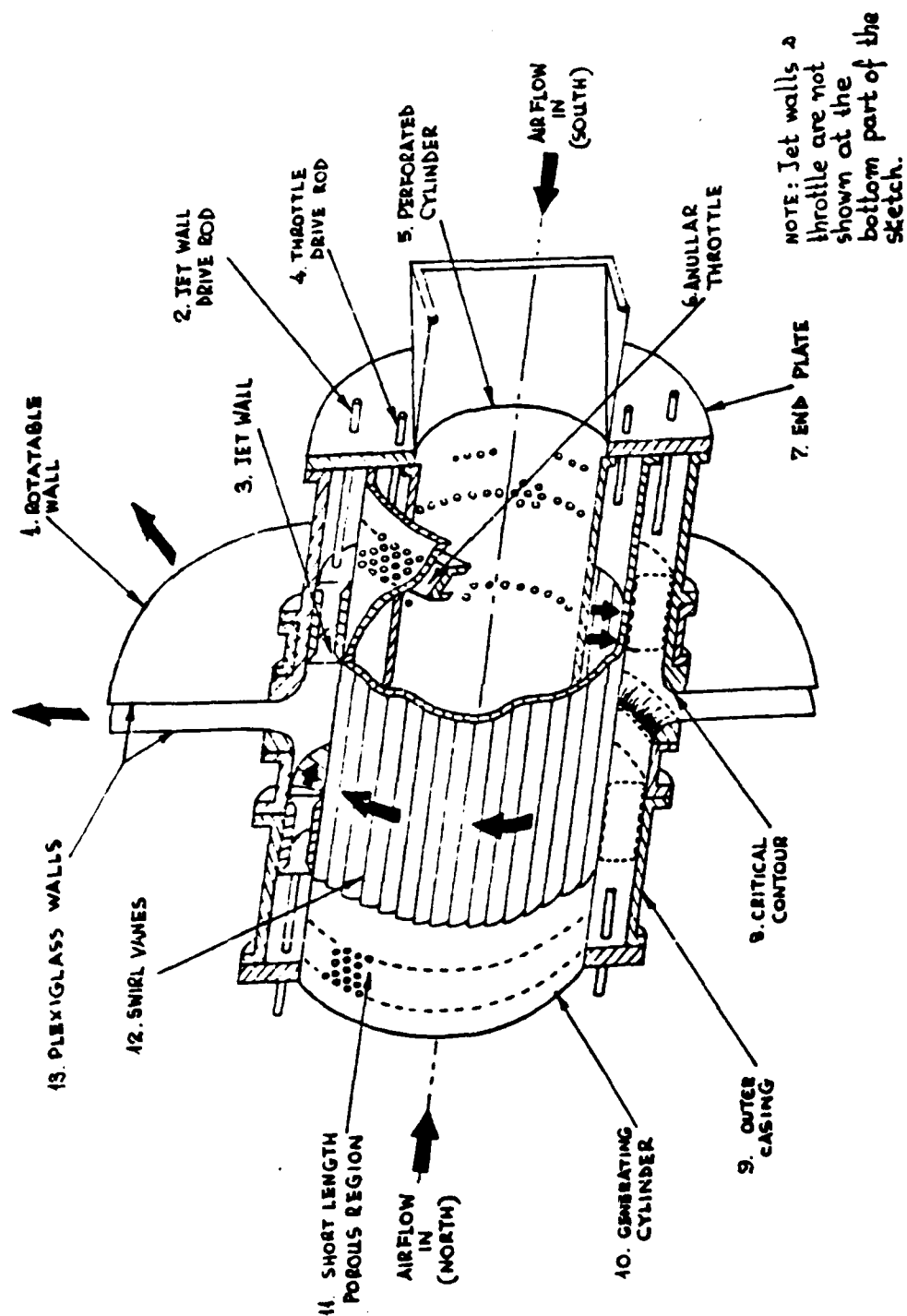
Figure 2. Schematic of CDTD Components

1. ROTATABLE WALL
2. JET WALL DRIVE ROD
3. JET WALL
4. THROTTLE DRIVE ROD
5. PERFORATED CYLINDER
6. ANULLAR THROTTLE
7. END PLATE
8. CRITICAL CONTOUR
9. OUTER CASING
10. GENERATING CYLINDER
11. SHORT LENGTH POROUS REGION
12. SWIRL VANES
13. PLEXIGLASS WALLS

AIR FLOW IN (SOUTH)

AIR FLOW IN (NORTH)

NOTE: Jet walls & throttle are not shown at the bottom part of the sketch.
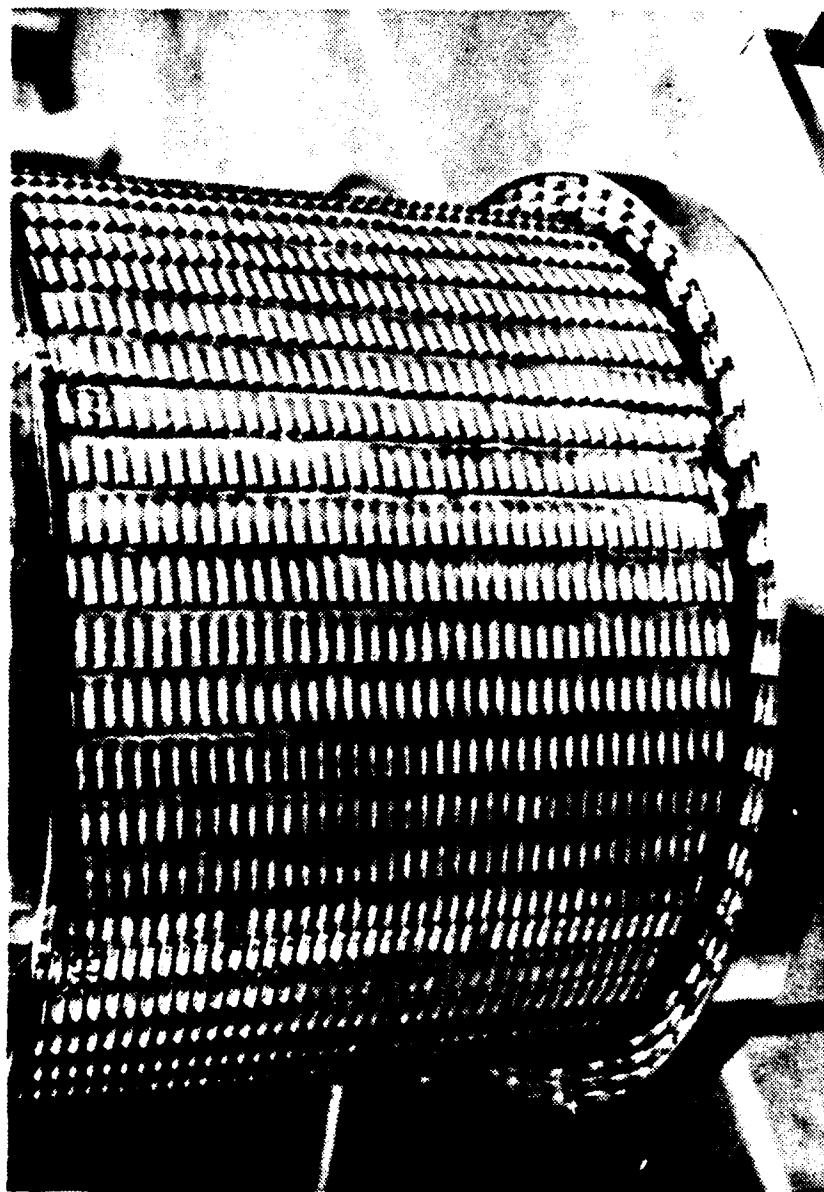
Figure 3. View of the Generating Cylinder and Jet Wall Hardware

SHROUD

Point	Z (FT)	R (FT)
1	.5	1.75
2	.75	1.75
3	1.0	1.75
4	1.25	1.75
5	1.5	1.75
6	1.75	1.75
7	1.7917	1.7556
8	1.8333	1.7754
9	1.875	1.8225
10	1.9917	1.8538
11	1.9042	1.8875
12	1.9083	1.90625
13	1.9167	2.0
14	1.9167	2.25
15	1.9167	2.5

HUB

Point	Z (FT)	R (FT)
1	.5	1.41667
2	.75	1.41667
3	1.0	1.41667
4	1.25	1.41667
5	1.5	1.41667
6	1.75	1.41667
7	1.8587	1.41667
8	1.9421	1.439
9	2.0031	1.5
10	2.0254	1.5833
11	2.0254	1.75
12	2.0254	2.
13	2.0254	2.4746

$L_t = 1.305"$

TEST SECTION INLET

$R_t = 24"$

$R_s = 21"$

$R = 19"$

$R_H = 17"$

GENERATING CYLINDER LOCATION

SHROUD R_1

(.5,1.5633)

HUB

Figure 4. CDTD Flowfield Model for MERIDL

40

FIGURE 5a

STREAMLINES GENERATED BY MERIDL

41
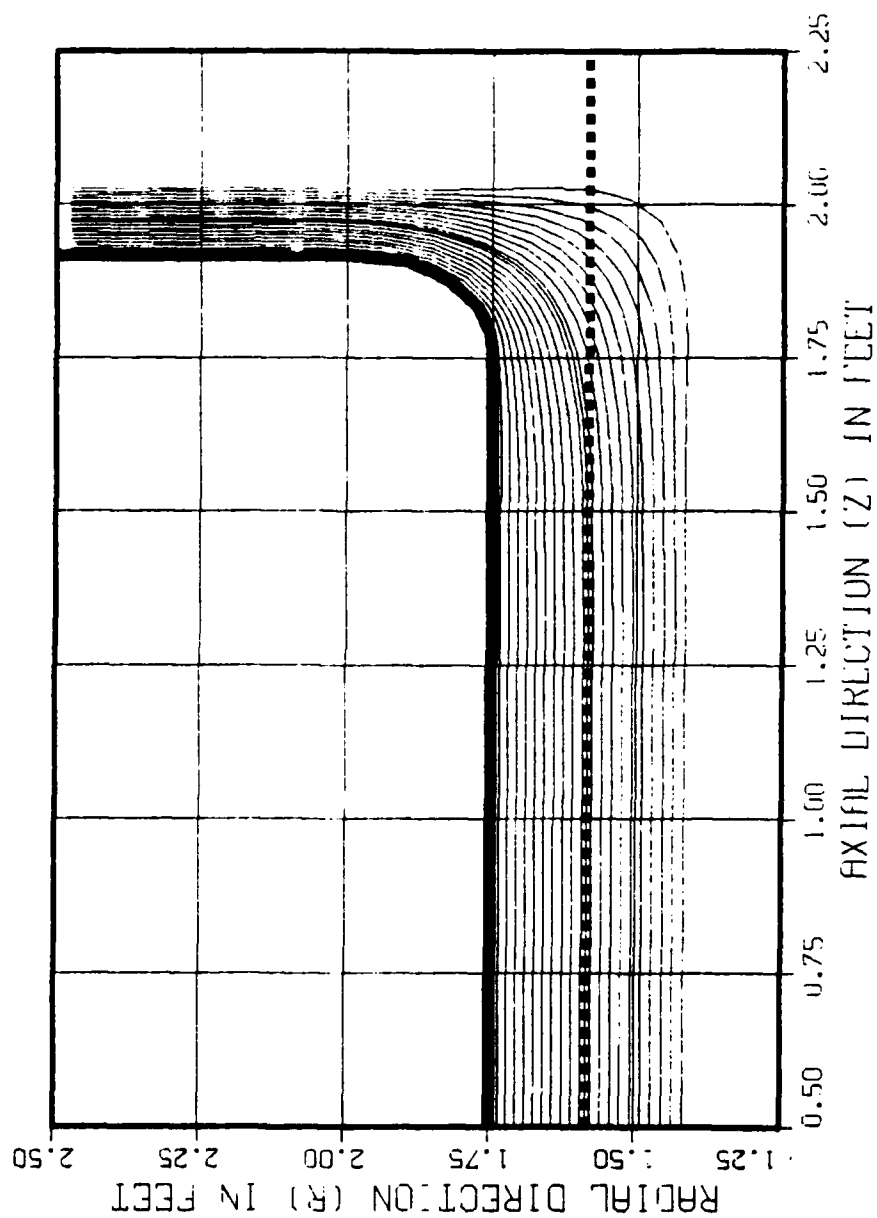
FIGURE 5b

STREAMLINES IN CONTRACTION CONE
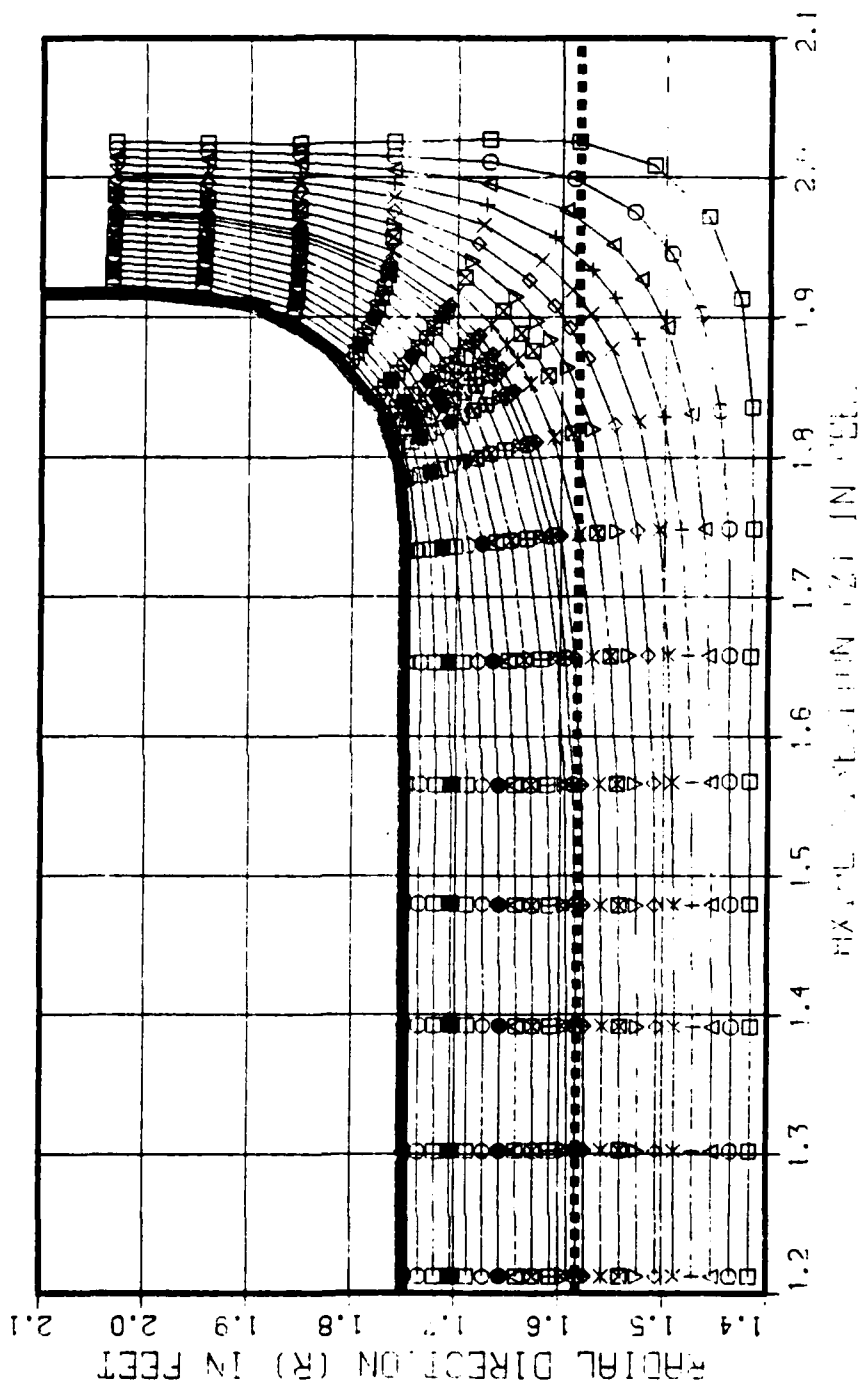
FIGURE 6

TOTAL VELOCITY VARIATION

ALONG CONTRACTION CONTOUR (STATIONS 14-24)

43
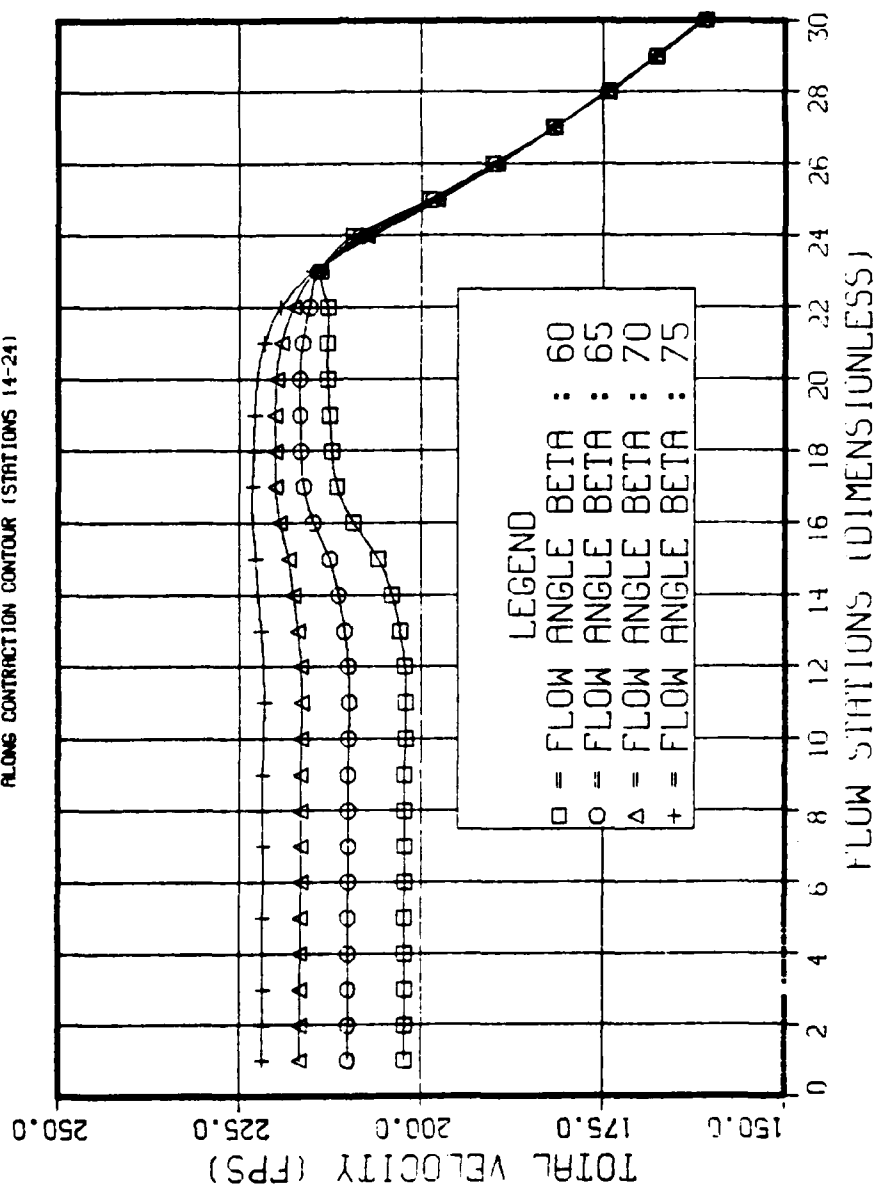
FIGURE 7

TOTAL VELOCITY VARIATION
ALONG - 0.0 (STATIONS 19-25)

44
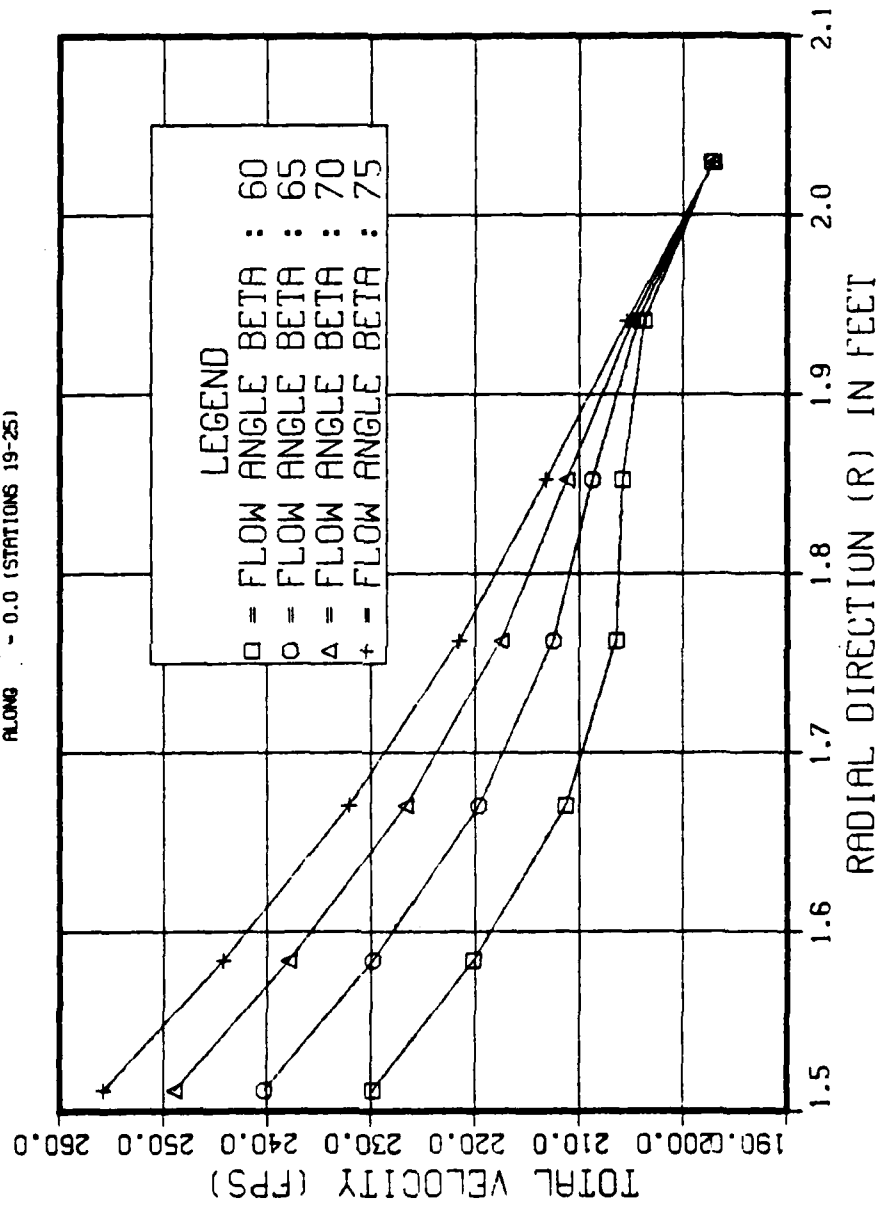
FIGURE 8

FLOW ANGLE VARIATION
ALONG - 0.0 (STATIONS 19-25)

LEGEND

□ = FLOW ANGLE BETA : 60
○ = FLOW ANGLE BETA : 65
△ = FLOW ANGLE BETA : 70
+ = FLOW ANGLE BETA : 75

RADIAL DIRECTION (R) IN FEET

FLOW ANGLE (DEGREES)

45
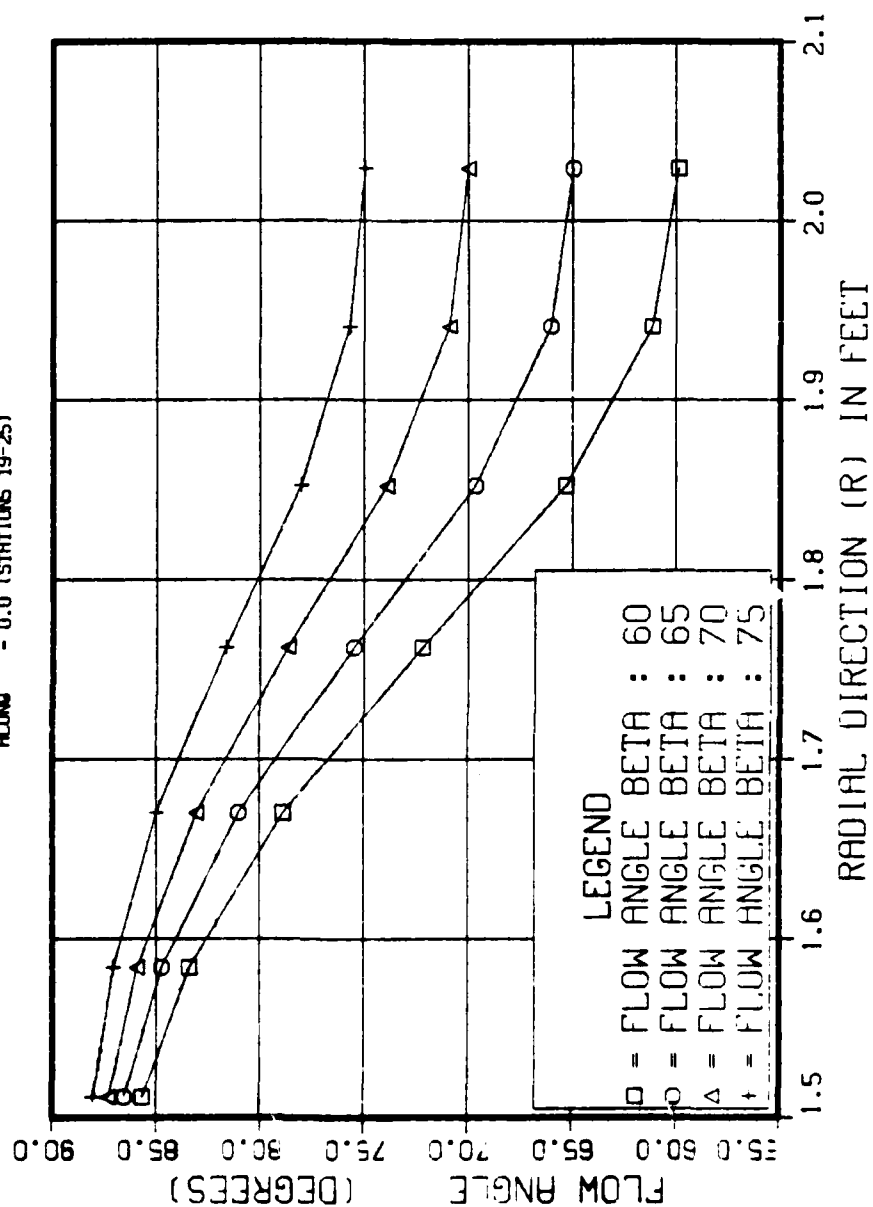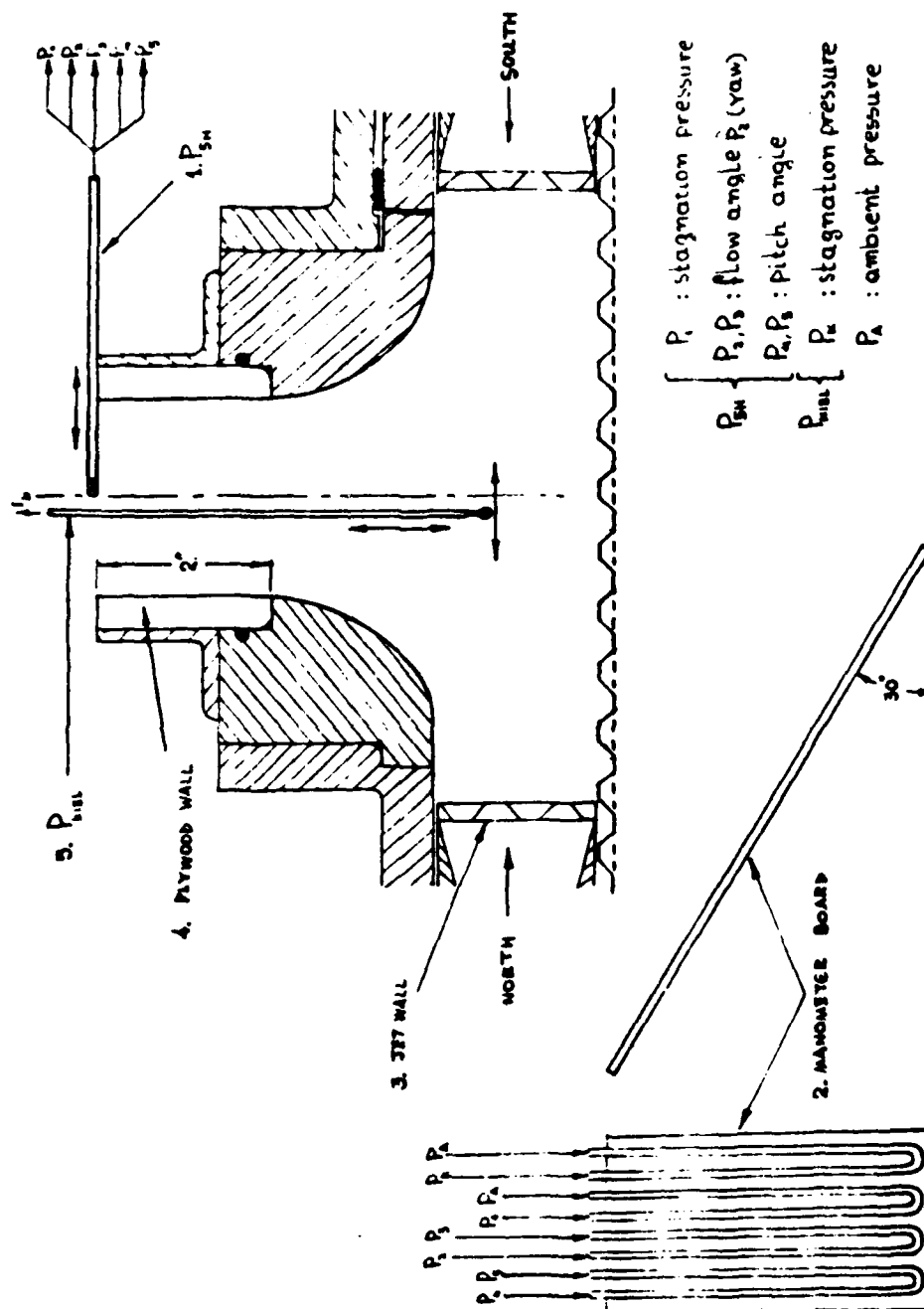
Figure 9. Installed Instrumentation for Preliminary Measurements

$P_{SM} \begin{cases} P_1 & : \text{stagnation pressure} \\ P_2, P_3 & : \text{flow angle } P_2 \text{ (yaw)} \\ P_4, P_5 & : \text{pitch angle} \end{cases}$

$P_{DISL} \begin{cases} P_M & : \text{stagnation pressure} \\ P_A & : \text{ambient pressure} \end{cases}$

1. P_{SM}

5. P_{DISL}

4. PLYWOOD WALL

3. JET WALL

NORTH

SOUTH

2'

30°

2. MANOMETER BOARD
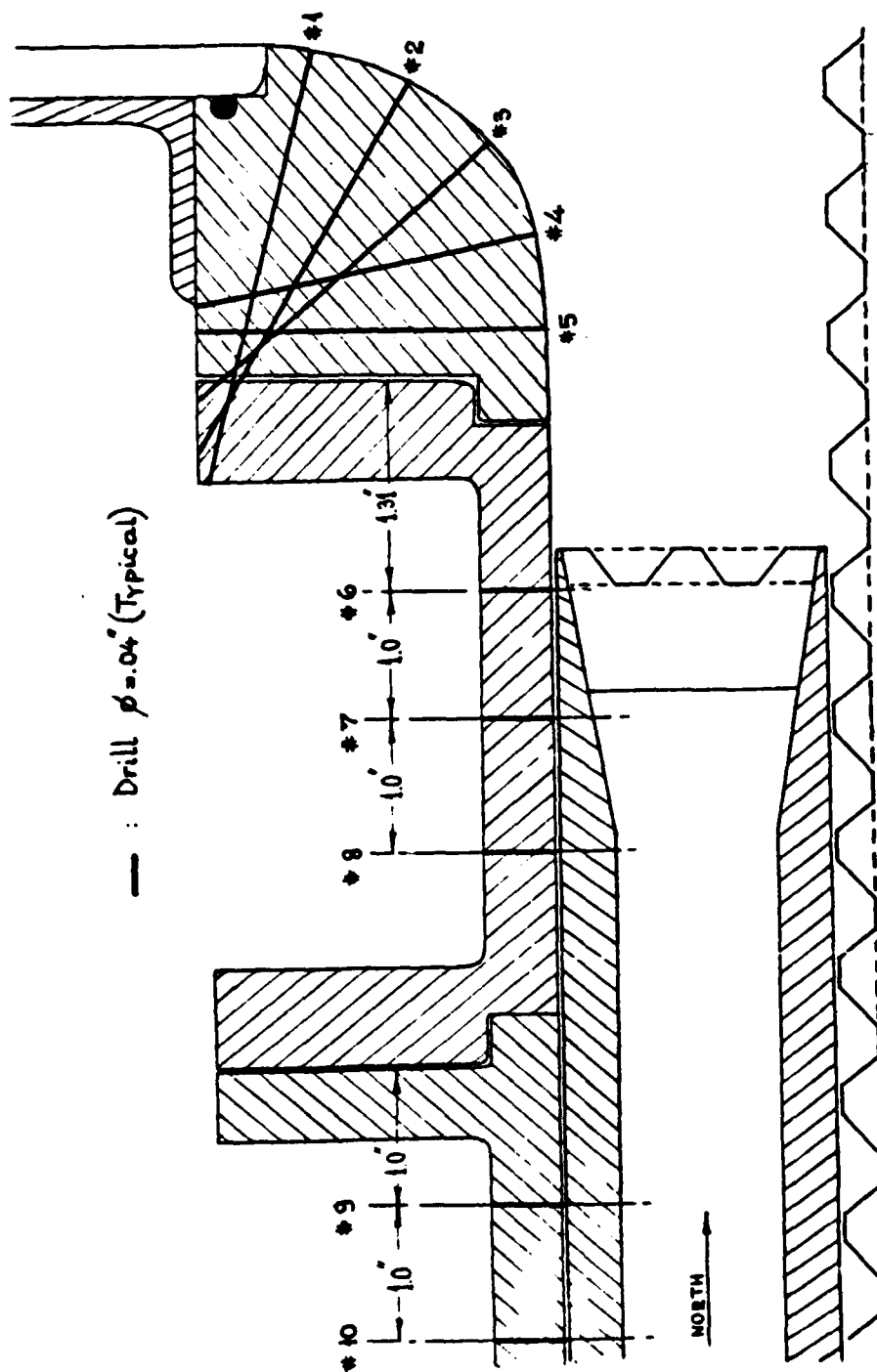
Figure 10a. Instrumentation Not Installed for Preliminary Measurements

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DRILL TAPS
#1 THRU #5,
#9 X #10

WEST

TOP

DRILL ONLY
TAP #9
(TYPICAL FOR TOP,
EAST X BOTTOM)

BOTTOM

SOUTH (ROTATING) WALL

EAST

TOP

BOTTOM

DRILL ONLY
TAPS #2,6,9
(TYPICAL FOR TOP,
EAST X BOTTOM)

WEST

DRILL A
COMPLETE
SET OF TAPS
(#1 - #10)

NORTH (FIXED) WALL
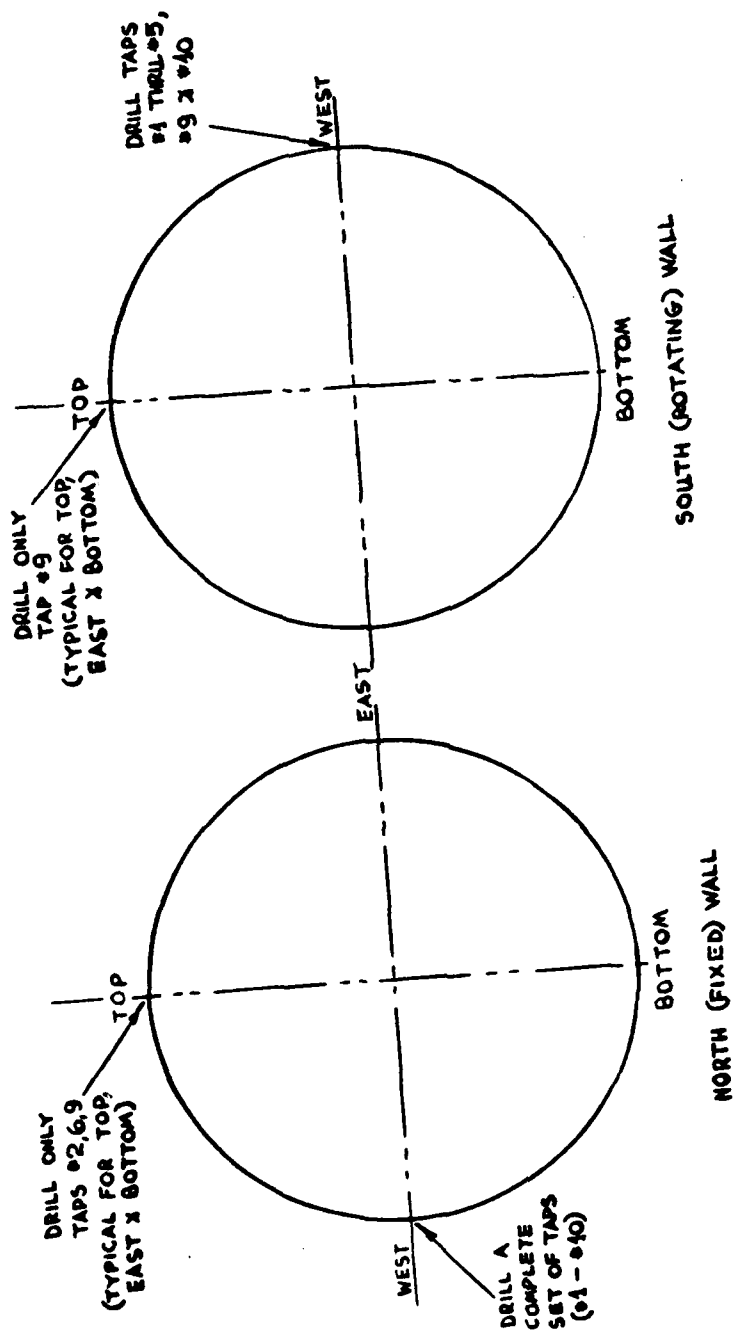
Figure 10b. Circumferential Arrangement of Pressure Taps

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FIGURE 11

JW SEALING EFFECT IN FLOW ANGLE (WEST)

JW SPACING : 8.0,THROTTLES : OPEN
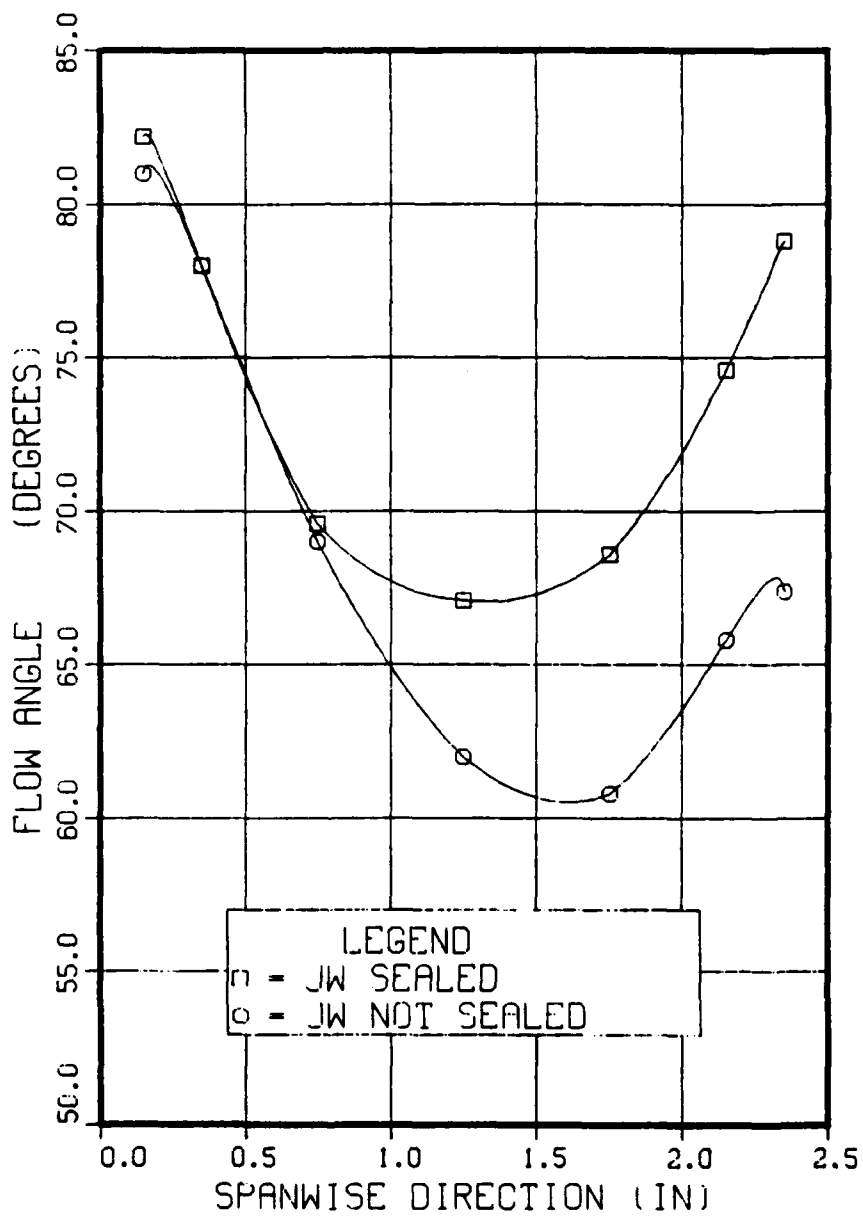
FIGURE 12

JW SEALING EFFECT IN FLOW ANGLE (WEST)

JW SPACING : 8.0,THROTTLES : CLOSED

LEGEND
□ = JW SEALED
○ = JW NOT SEALED
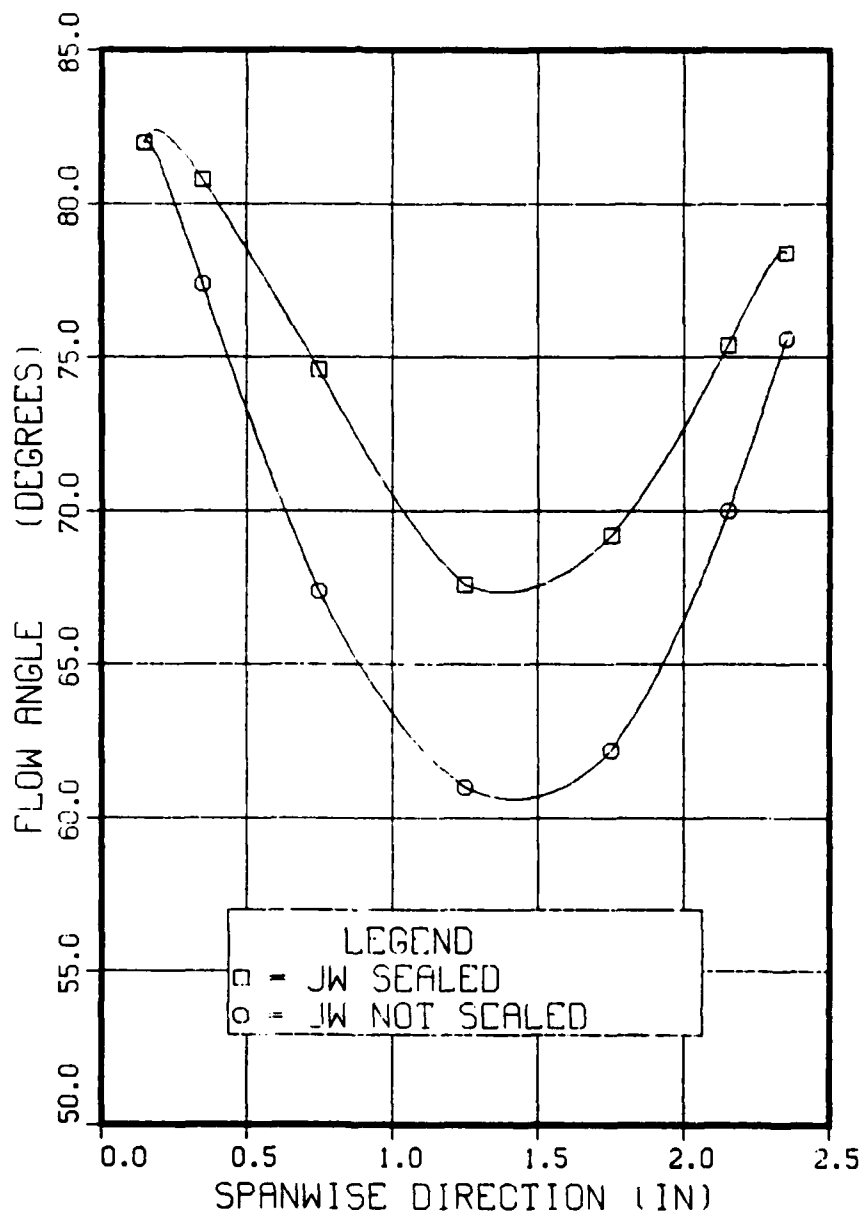
FIGURE 13

JW SEALING EFFECT IN TOTAL PRESSURE (WEST)

JW SPACING : 8.0,THROTTLES : OPEN

LEGEND
□ = JW SEALED
○ = JW NOT SEALED
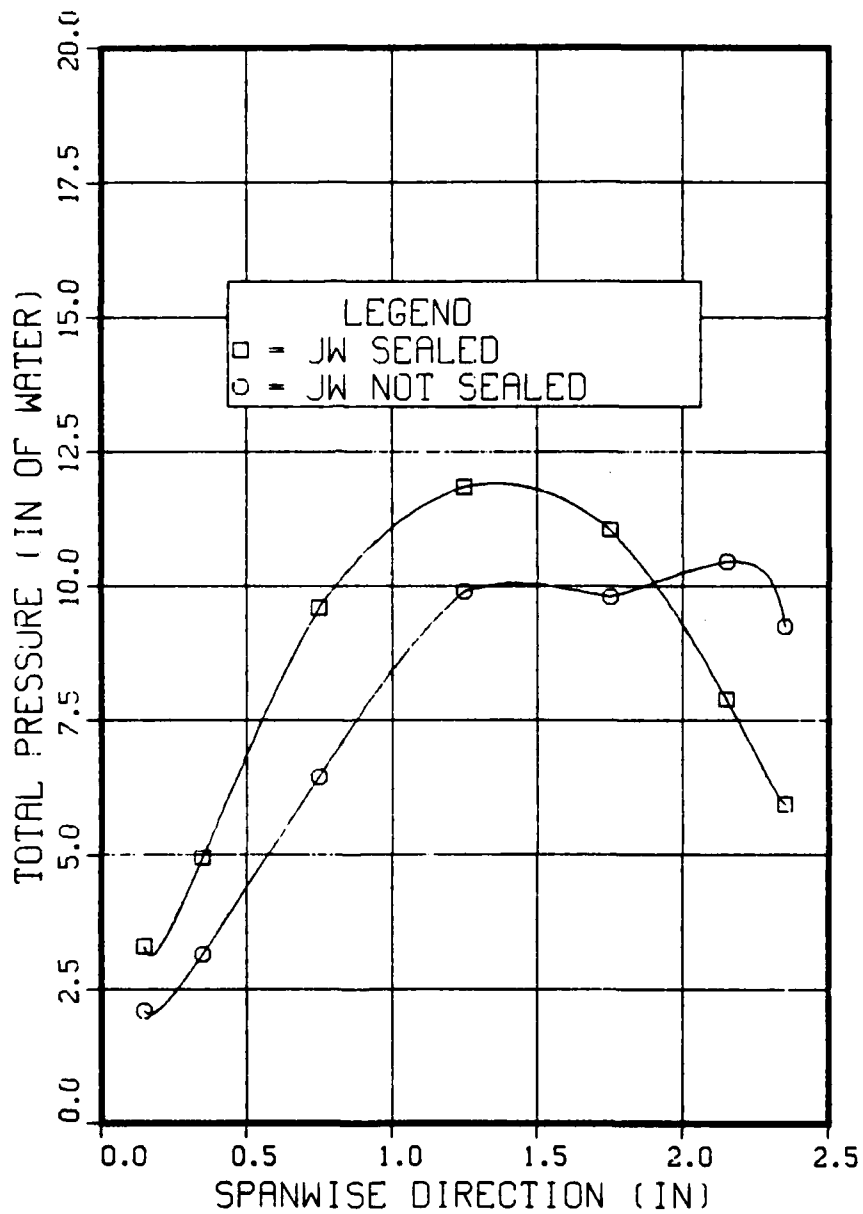
FIGURE 14

JW SEALING EFFECT IN TOTAL PRESSURE (WEST)
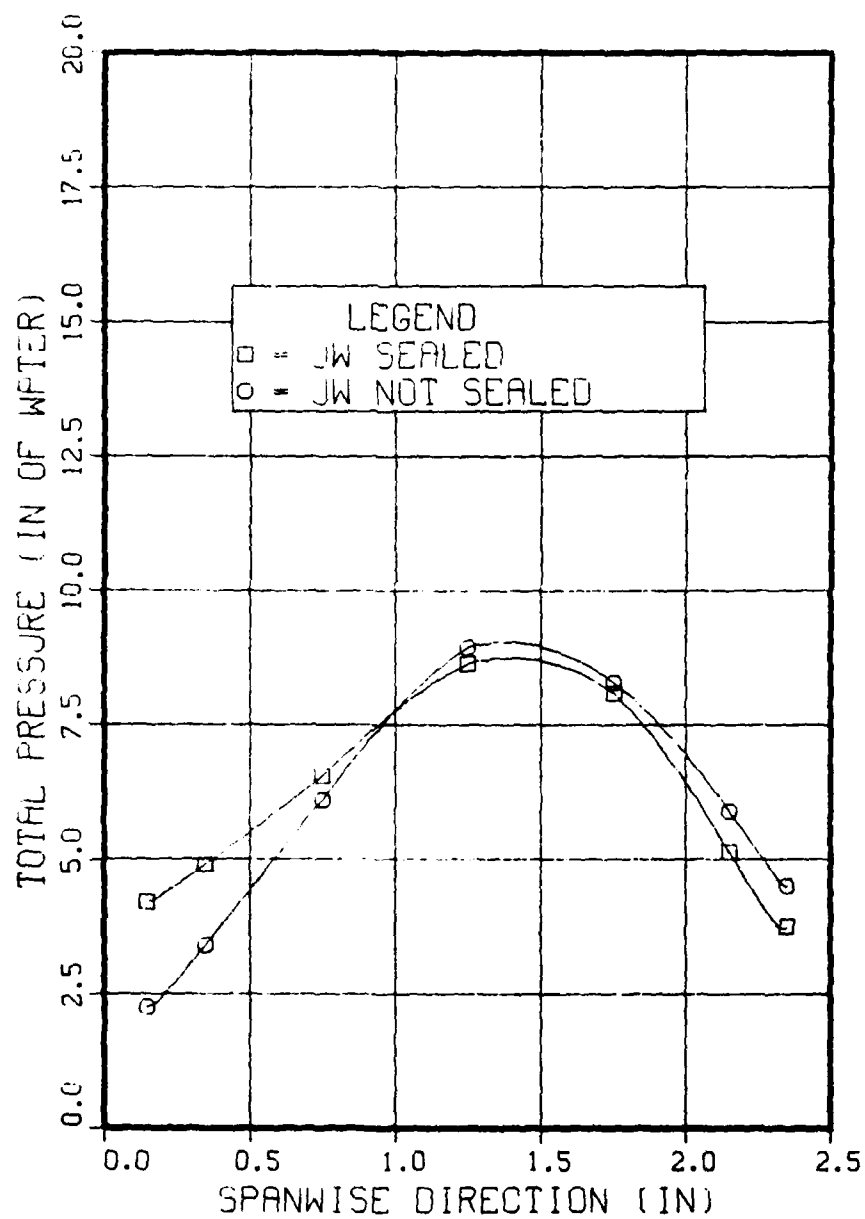
JW SEALING : S.O.,THROTTLES : CLOSED

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FIGURE 15

CIRCUMFERENTIAL MEASUREMENTS (FLOW ANGLE)

IN SPACING = H.0 IN, THROTTLES = OPEN

53
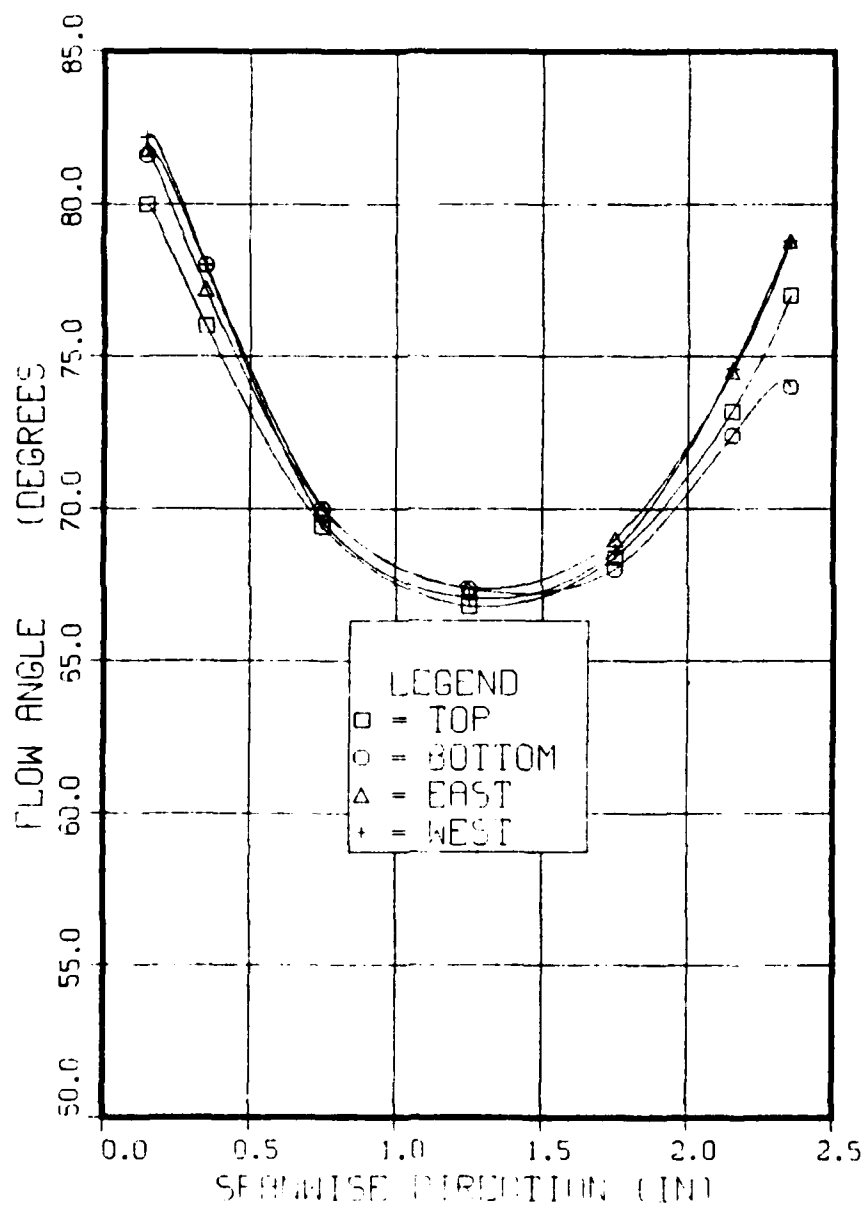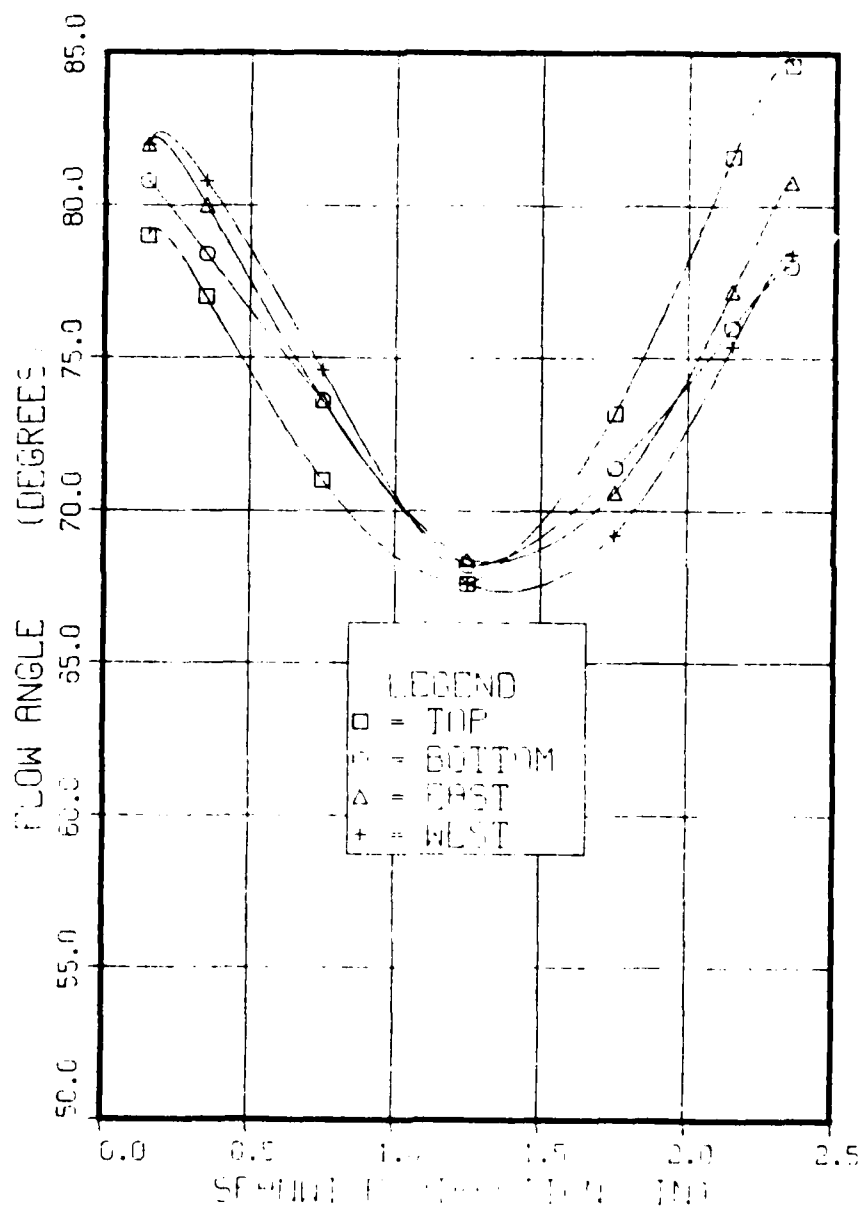
Figure 16

FIGURE 17

CIRCUMFERENTIAL MEASUREMENT - PRESSURE

IN SPACING 0.1 IN ,THROTTLES OPEN
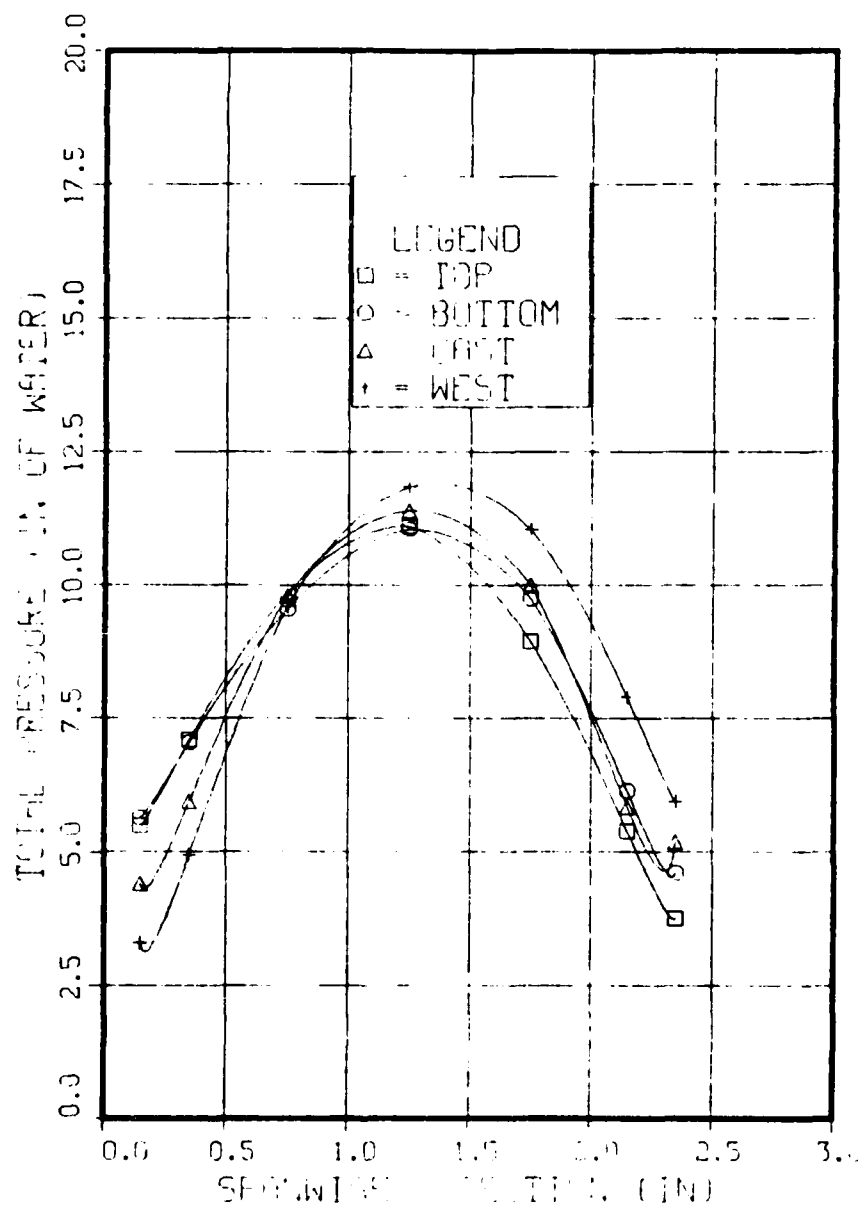
FIGURE 18

CIRCUMFERENTIAL MEASUREMENTS (PRESSURE)

IN BLENDING RPM IN THROTTLE : CLOSED
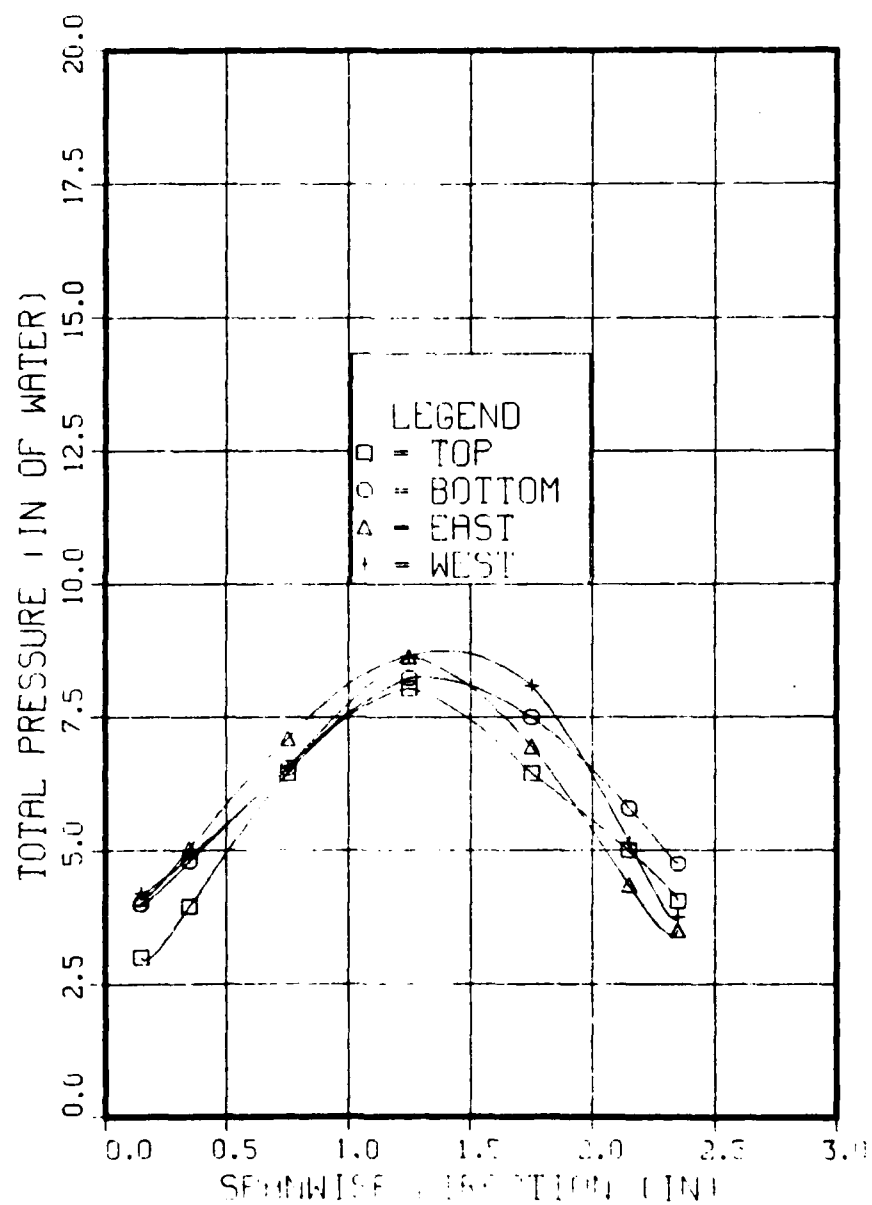
FIGURE 19

JW SPACING EFFECT IN FLOW ANGLE (WEST)

THROTTLES : OPEN

LEGEND
□ = JW SPACING: 24.375
○ = JW SPACING: 8.0
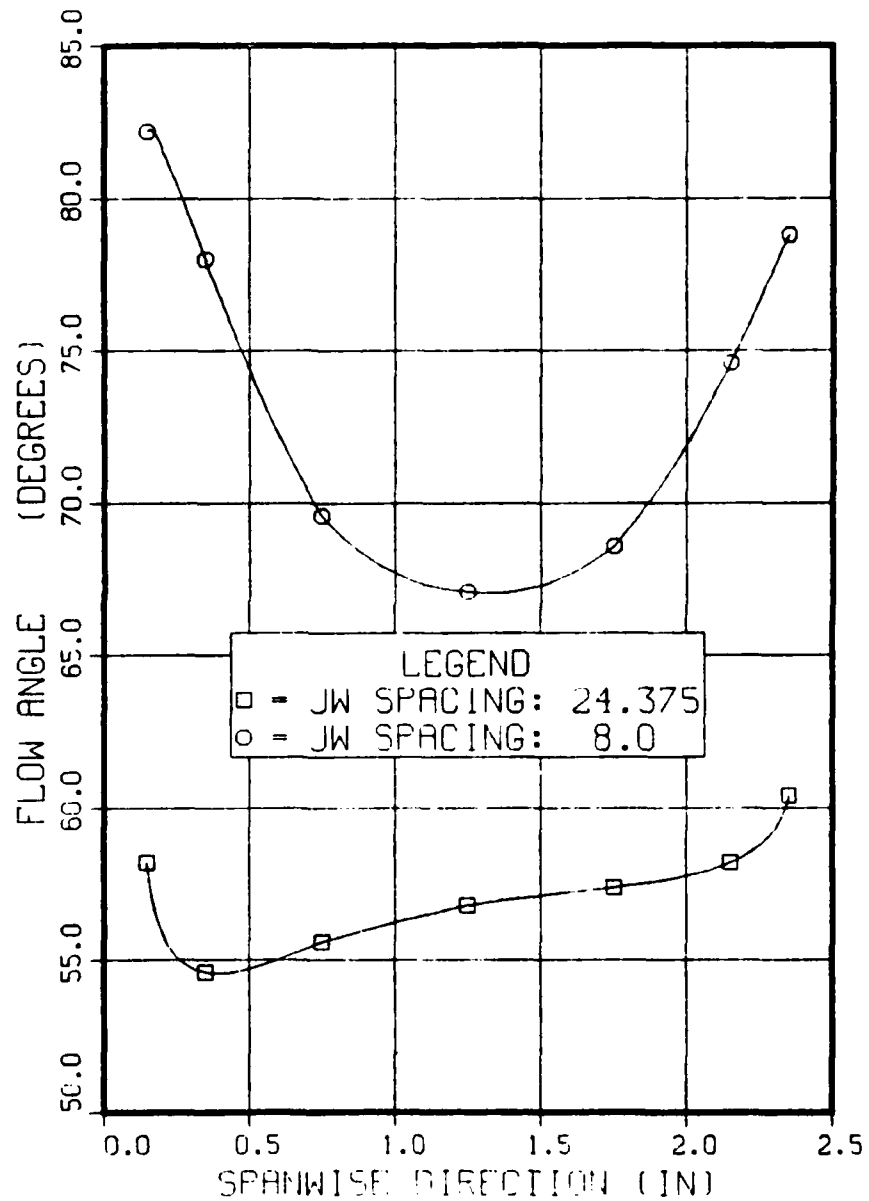
Figure 20

JW SPACING EFFECT IN TOTAL PRESSURE (WEST)

THROTTLES : OPEN
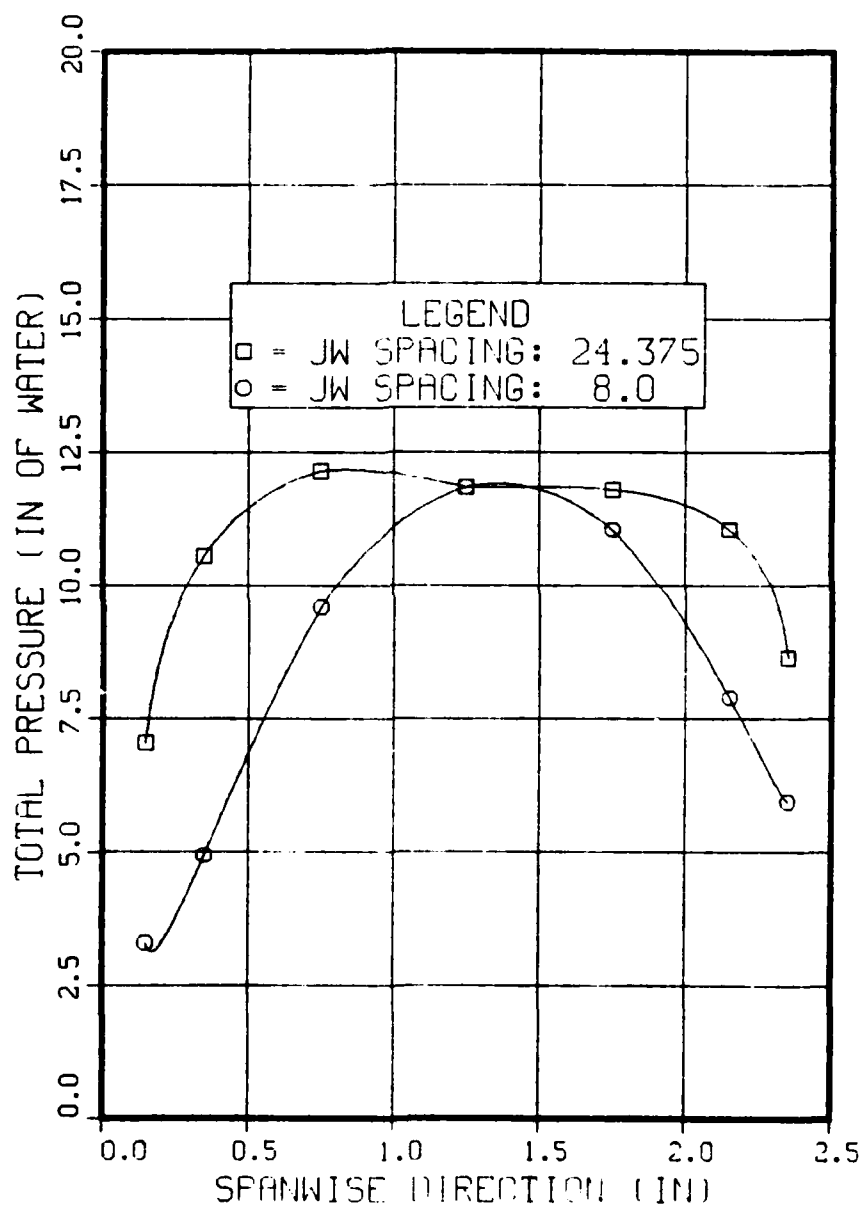
FIGURE 21

THROTTLING EFFECT IN FLOW ANGLE (WEST)

JW SPACING : 24.375 IN
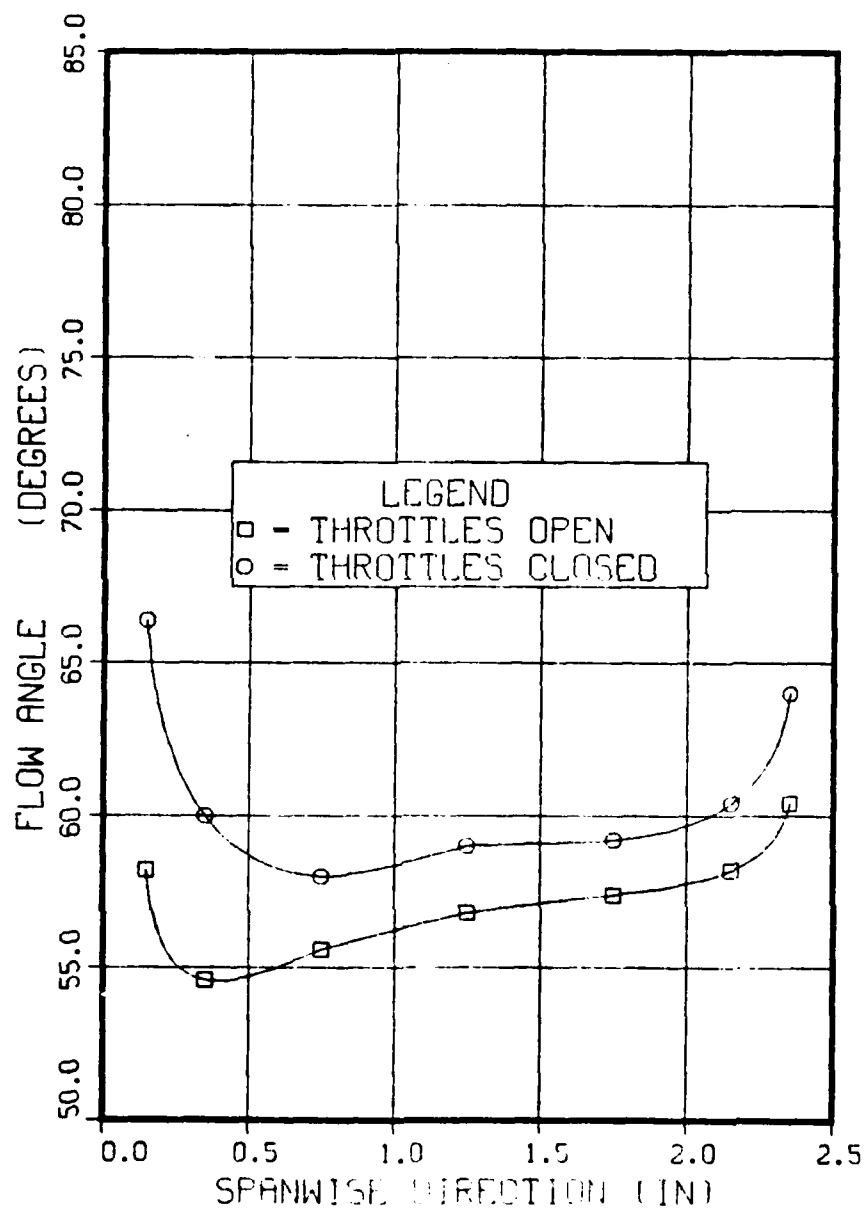
FIGURE 22

THROTTLING EFFECT IN FLOW ANGLE (WEST)

JW SPACING : 8.0 IN

60
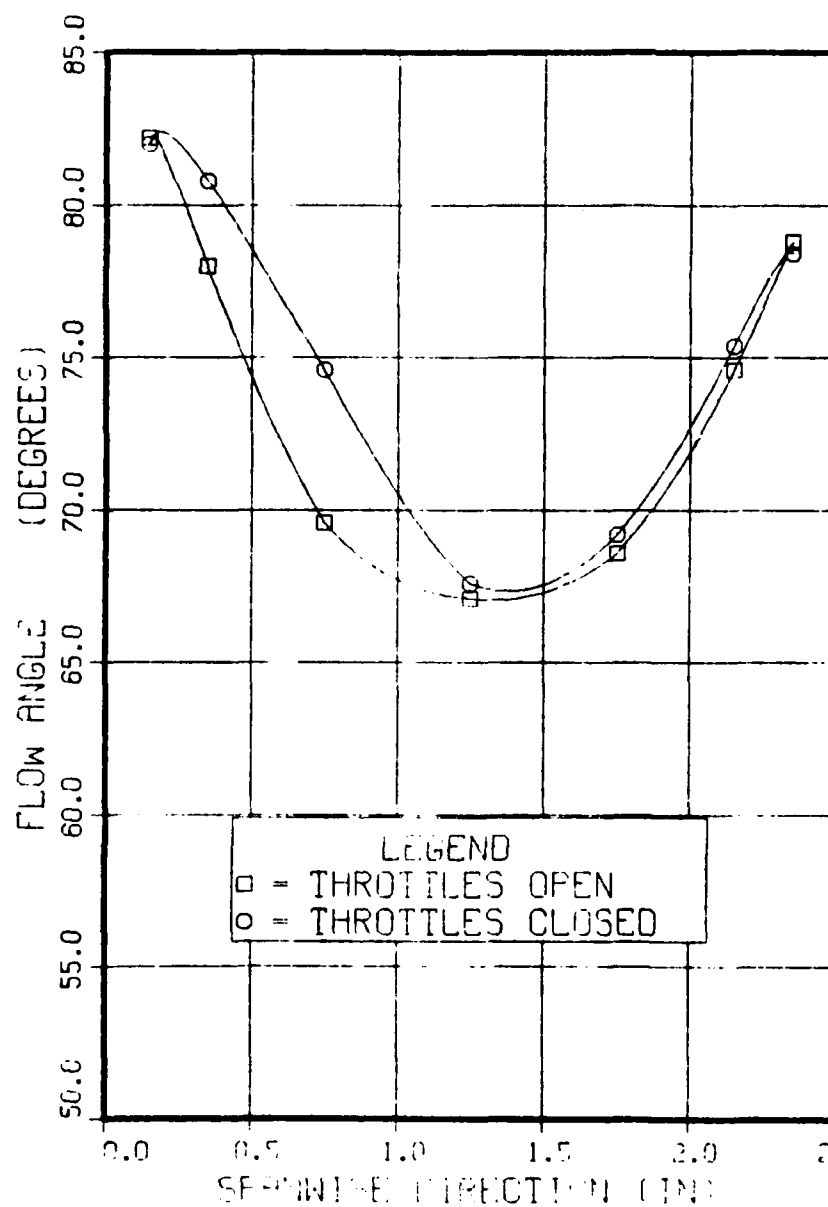
FIGURE 23

THROTTLING EFFECT IN TOTAL PRESSURE (WEST)
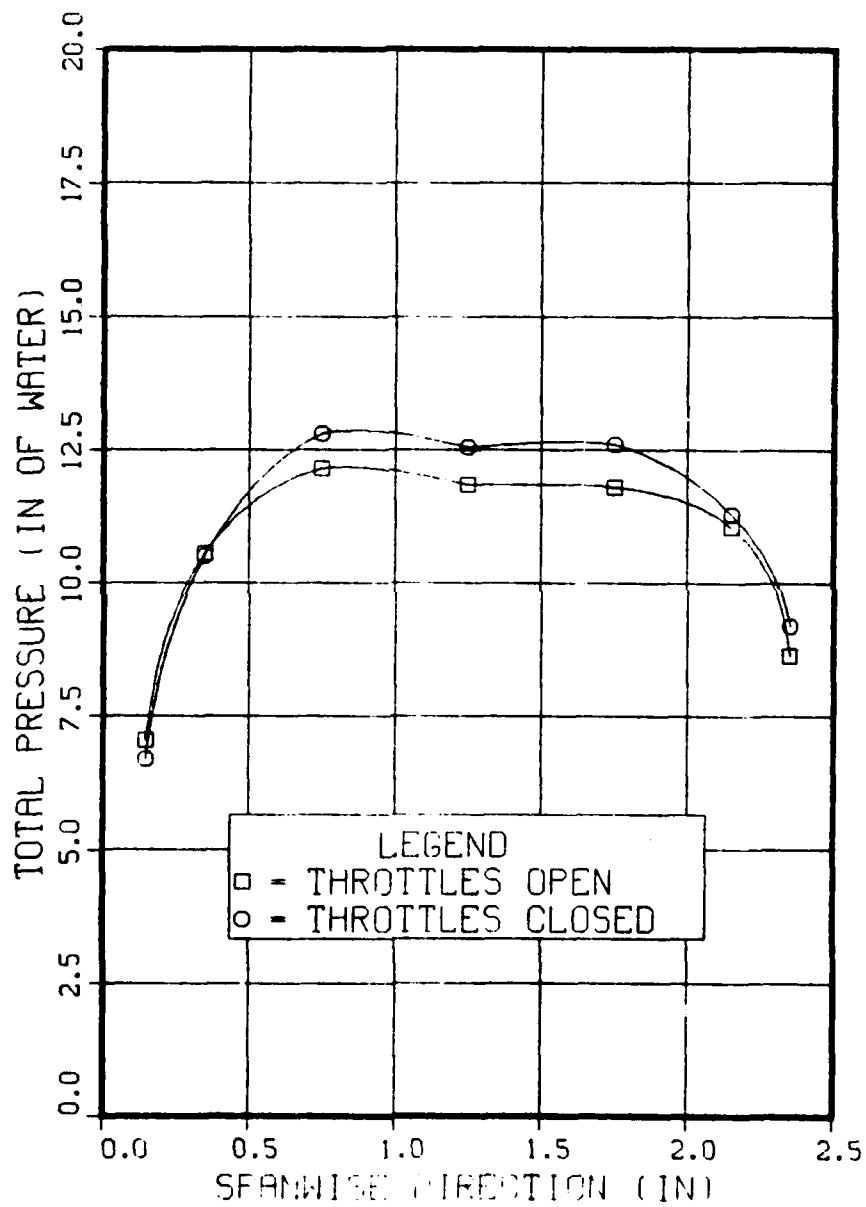
ON SPACING : 24.375 IN

FIGURE 24

THROTTLING EFFECT IN TOTAL PRESSURE (WEST)

IN SPACING : 8.0 IN
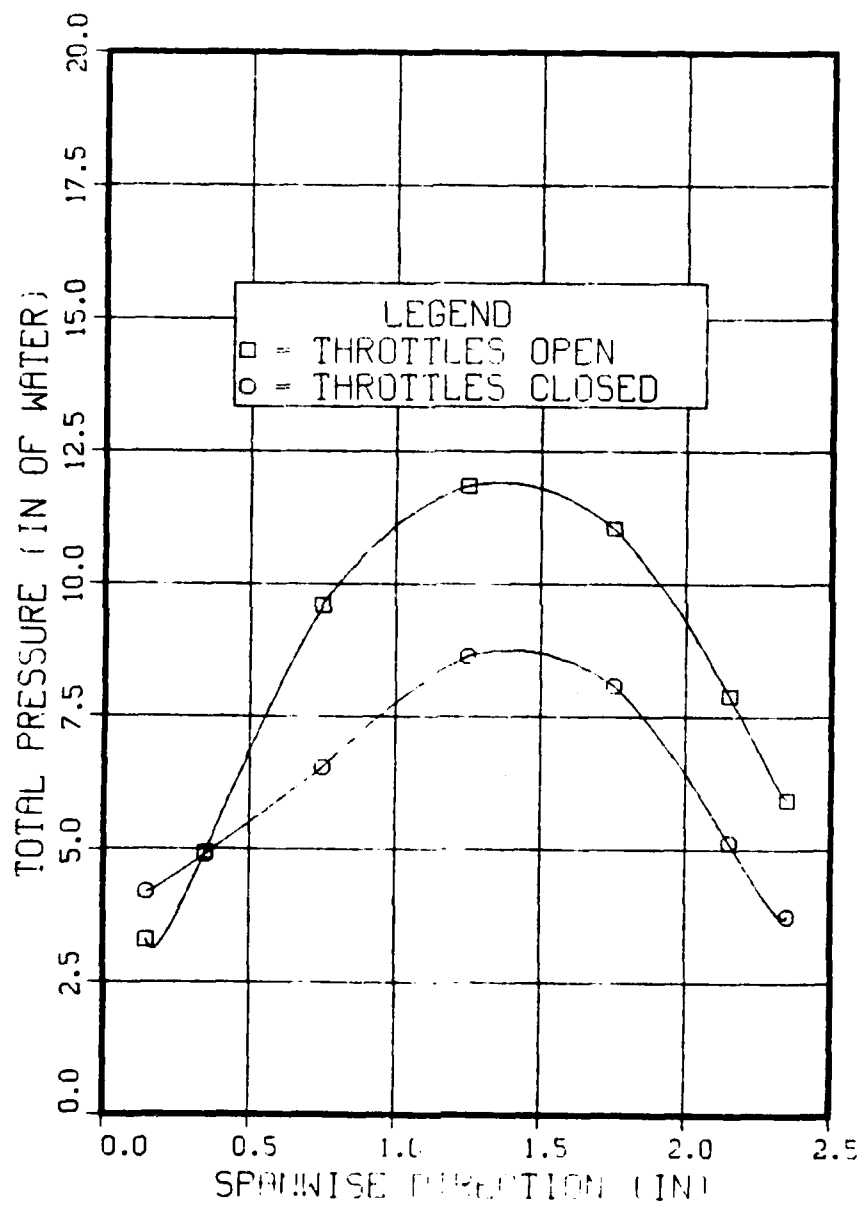
FIGURE 25

CIRCUMFERENTIAL MEASUREMENTS OF FLOW ANGLE

IN SPACING = 24.375 IN ,THROTTLE = OPEN
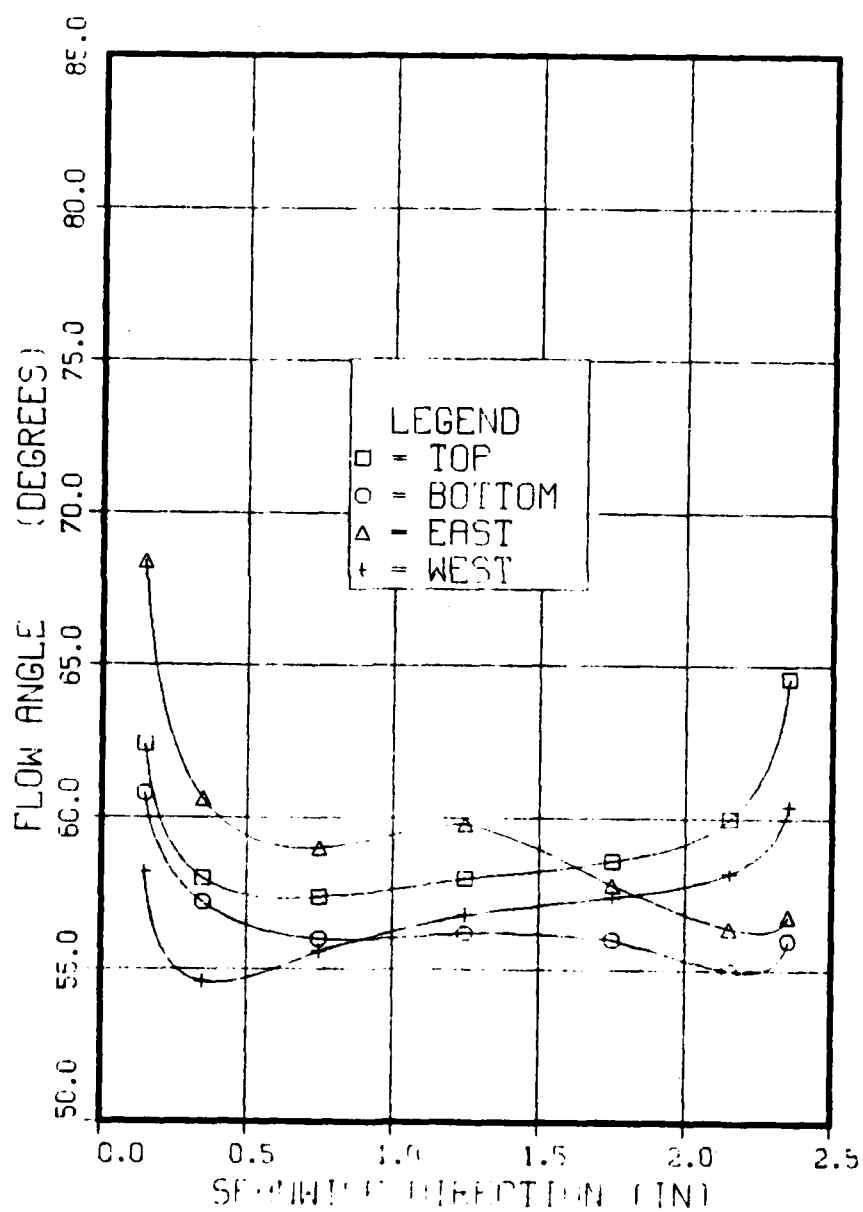
FIGURE 26

CIRCUMFERENTIAL MEASUREMENTS (FLOW ANGLE)

JW SPACING : 24.375 IN, THROTTLES : CLOSED

64
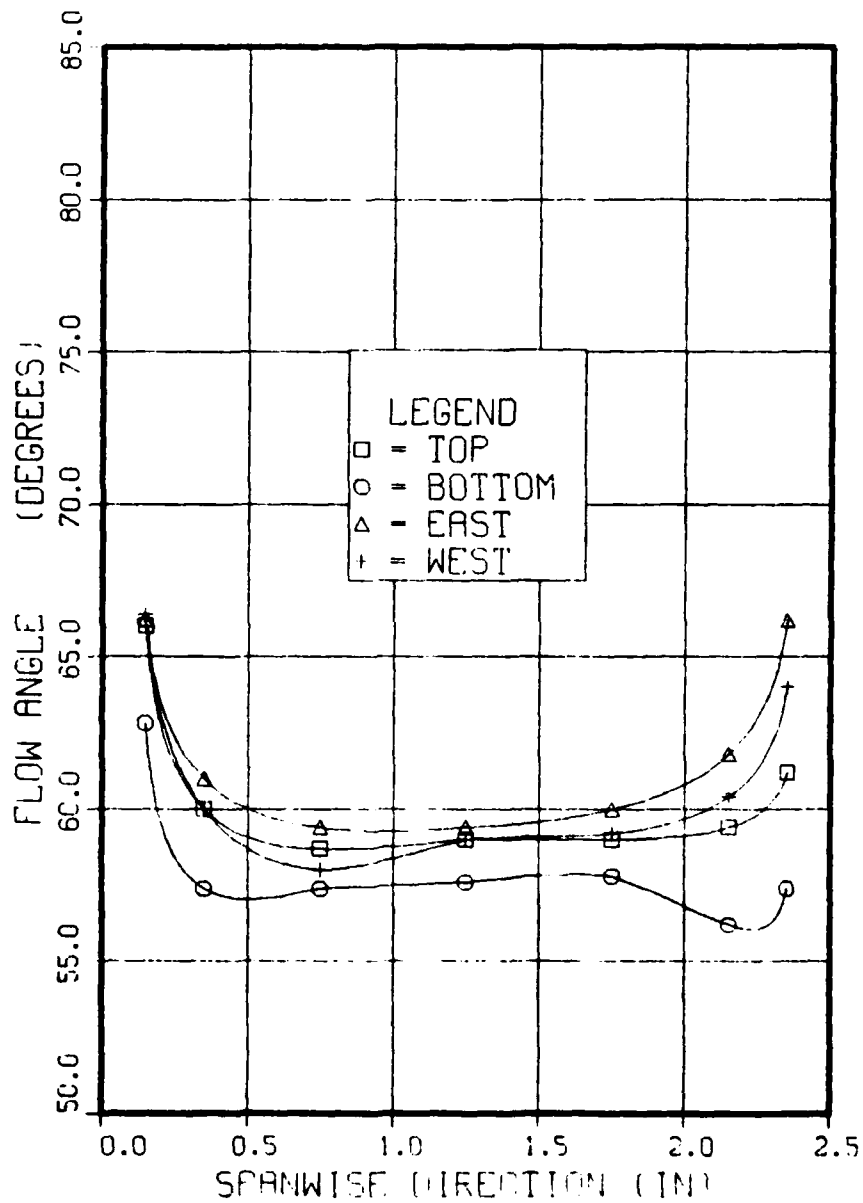
FIGURE 27

CIRCUMFERENTIAL MEASUREMENTS (PRESSURE)

IN SPACING : 24.375 IN ,THROTTLES : OPEN
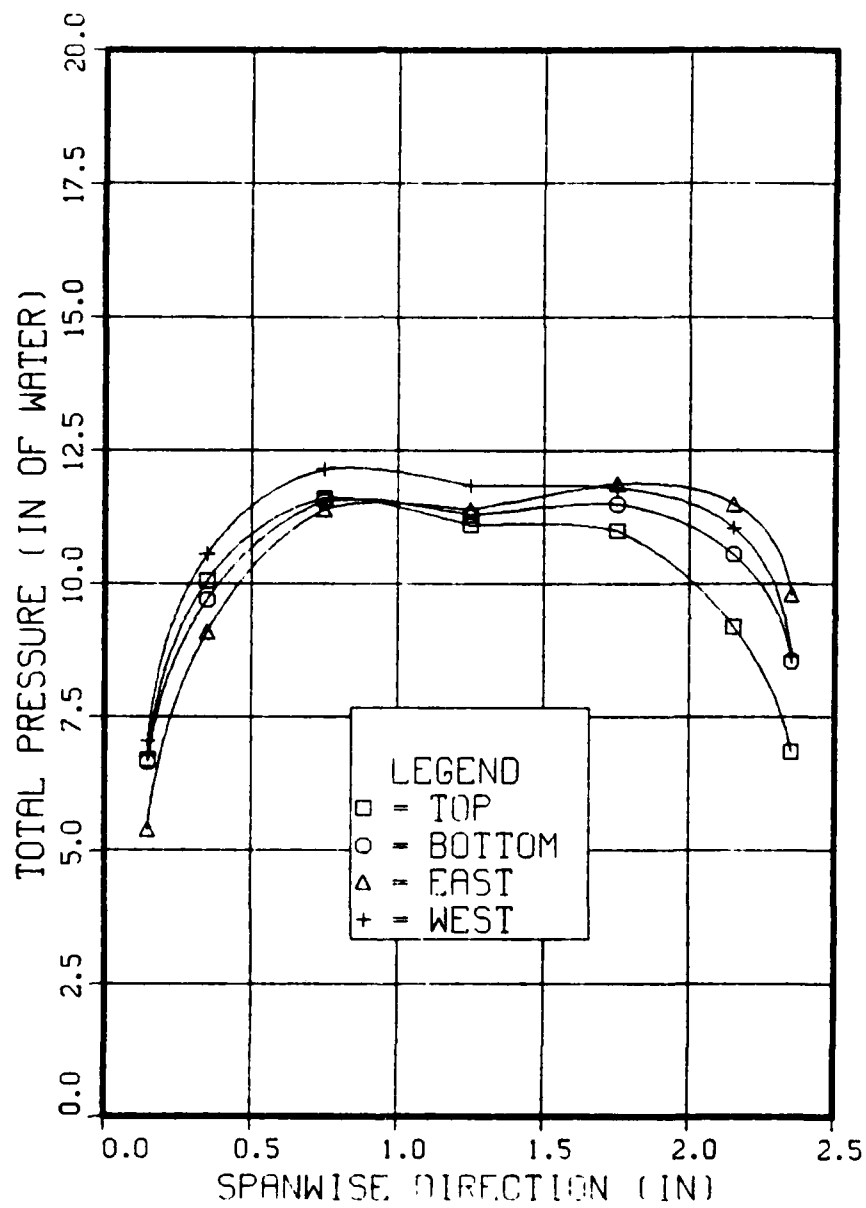
FIGURE 28

CIRCUMFERENTIAL MEASUREMENTS (PRESSURE)

IN SPACING : 24.375 IN ,THROTTLES : CLOSED

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FIGURE 29

CUMBINED PLOT OF MEASURED

AND CALCULATED FLOW ANGLES.

LEGEND
□ - DESIGN (L_2 -2.0 IN)
○ - DESIGN (L_2 -2.62 IN)
△ - MEASURED (Average)
+ - CV ANALYSIS
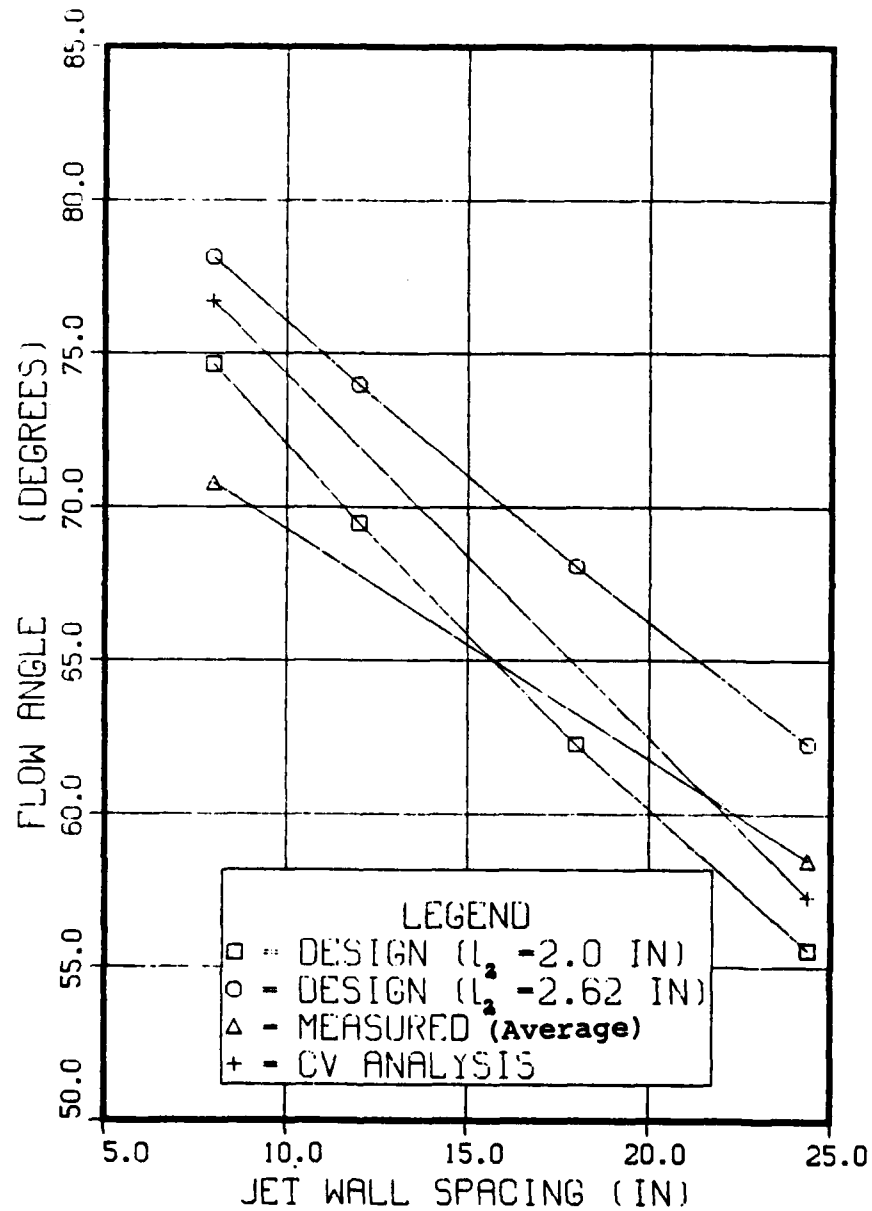
APPENDIX A

CDTD DESIGN CALCULATIONS

Assumptions:

1. The velocity coming out of the JW is the same as at the GC surface (Fig. A1).

2. No losses.

3. Constant density (incompressible) flow.

The velocity components are given by:

$$V_{R_i} = V_i \cos \beta_i \qquad\qquad A(1)$$

and

$$V_{\theta_i} = V_i \sin \beta_i \qquad\qquad A(2)$$

applying continuity between stations 1 and 2 (Fig. A1).

$$V_{\theta_1} \cdot Z \cdot A_{SV} \cdot N \cdot L_1 + V_{\theta_1} \cdot A_{JW} = V_{R_2} \cdot R_2 (2\pi L_2)$$

so that

$$L_1 = \frac{V_{R_2} R_2 (2\pi L_2) - V_{\theta_1} A_{JW}}{V_{\theta_1} Z A_{SV} N} \qquad\qquad A(3)$$

Applying conservation of angular momentum:
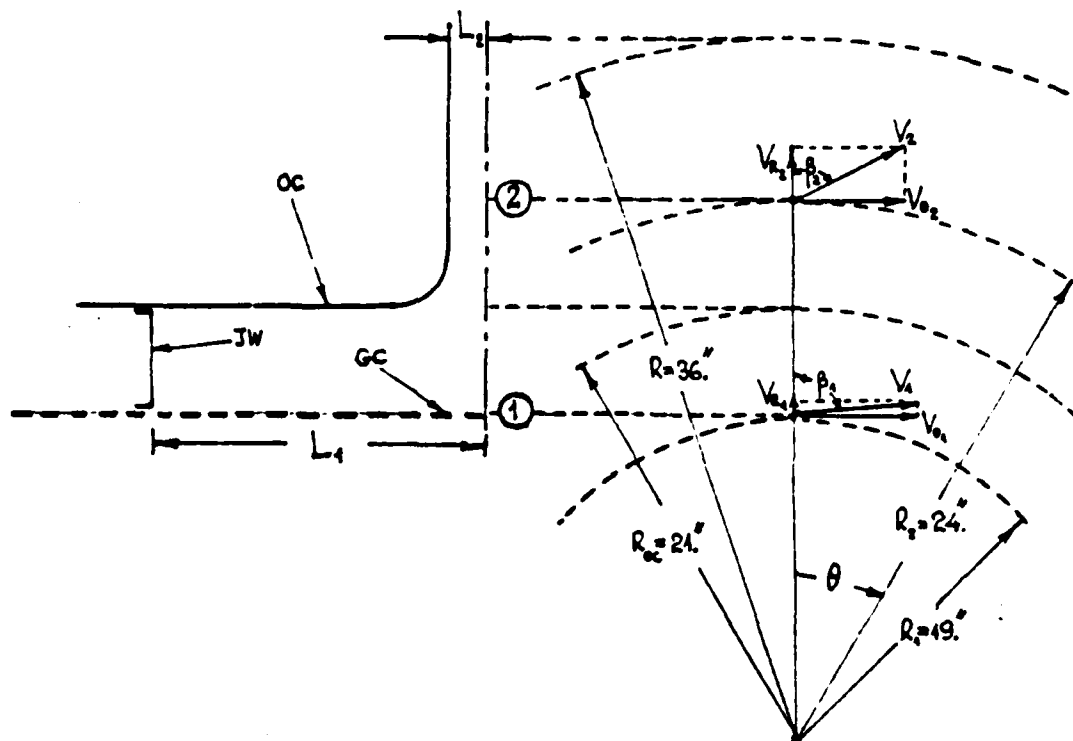
Figure A1. CDTD Schematic for the Design Calculations

$$V_{\theta_1} R_1 \;=\; V_{\theta_2} R_2 \hspace{3cm} A(4)$$

or

$$V_{\theta_1} \;=\; V_{\theta_2} \frac{R_2}{R_1} \hspace{3cm} A(4.1)$$

and substituting in A(3) for V_{θ_1} from Eq. A(4.1)

$$L_1 \;=\; \{ \frac{R_1 (2\pi L_2)}{Z A_{SV} N} \} \frac{V_{R_2}}{V_{\theta_2}} \;-\; \frac{A_{JW}}{Z A_{SV} N} \hspace{2cm} A(5)$$

Substituting into Eq. A(5) the values for R_1, L_2, Z, A_{SV}, N, and A_{JW}, a linear relation is established between L_1 and $\cot \beta_2$; thus

$$L_1 = 25.97 \cot \beta_2 - 1.458 \qquad A(6)$$

where data have been used for the as-manufactured test section span ($\ell_2 = 2.61"$) and the short plywood walls.

For the designed span ($\ell_2^* = 2"$), and plexiglass walls installed:

$$L_1^* = 19.9 \cot \beta_2 - 1.458 \qquad A(7)$$

Equations A(6) and A(7) can also be solved for β_2 and β_2^*; thus

$$\beta_2 = \cot^{-1}(.0385L_1 + .056) \qquad A(8)$$

$$\beta_2 = \cot^{-1}(.05025L_1^* + .07326) \qquad A(9)$$

Using Equations A(8) and A(9) the following Table Al is obtained:

TABLE A1

FLOW ANGLES (β_2) AND CORRESPONDING
JW SPACING OBTAINED FROM EQUATIONS
A(8) AND A(9)

β_2	ℓ_1 (in)	β_2^*	ℓ_1^* (in)
65.	21.304	65	15.643
70.	15.989	70	11.57
75.	11.001	75	7.748
62.29	24.375	55.56	24.375
68.075	18.00	62.27	18.00
73.987	12.00	69.456	12.00
78.14	8.00	74.663	8.00
79.2	7.00	76.01	7.00

APPENDIX B

FLOW MODELING CALCULATIONS FOR MERIDL INPUT

Assumptions:

1. Free vortex flow: $V_{i} R_{i}$ = constant (from hub to tip at a certain station) and V_Z = constant with radius at constant Z.

2. Constant density ρ = .076 LB_m/FT^3.

3. Total velocity at the inlet of the TS, V_2 = 200 FPS

4. Axisymmetric flow.

5. Flow enters from Station 1-1 (Fig. 4) with constant whirl.

Flow Area at TS Inlet

$$A_2 = 2\pi R_2 L_2 = 1.3666 \ FT^2$$

$$V_{R_2} = V_2 \cos \beta_2 = 200 \cos \beta_2 \ FPS$$

$$\dot{m}_2 = \rho V_{R_2} A_2 = 20.772 \cos \beta_2 \ Lbm \cdot sec^{-1}$$

Flow Area at Inlet (Station 1-1)

$$A_{IN} = \pi(R_S^2 - R_H^2) = 3.316 \ FT^2$$

$$V_Z = constant$$

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Applying continuity between Station 1-1 and at the inlet
of the test section:

$$\dot{m} = \rho_1 V_Z A_{IN} = \rho_2 V_{R_2} A_2 \qquad \text{B(1)}$$

so that

$$V_Z = V_{R_2} \frac{A_2}{A_{IN}} = .412 \, V_{R_2} \qquad \text{B(2)}$$

Free vortex flow implies that

$$V_{\theta_1} R_1 = V_{\theta_2} R_2 \qquad \text{B(3)}$$

and solving for V_{θ_1} and inserting values for R_1 and R_2,

$$V_{\theta_1} = 1.263 \, V_{\theta_2} \qquad \text{B(3.1)}$$

Also,

$$V_{\theta_2} = V_2 \sin \beta_2 = 200 \sin \beta_2 \, \text{(ft/sec)} \qquad \text{B(4)}$$

For selected values of β_2 the following Table B1 was
constructed, using the above equations to obtain the corres-
ponding whirl $(R_i V_{\theta_i})$ and the mass flow rate $(\dot{m})$, required
as input to MERIDL.

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TABLE B1

CALCULATED INPUT PARAMETERS FOR MERIDL CODE

β_2 (Deg)	V_{R_2} (Ft/Sec)	$\dot{m}$ (lbs/Sec)	V_{θ_2} (Ft/Sec)	$V_{\theta_2}R_2$ (Ft^2/Sec)
60	100	.3225	173.21	346.4
65	84.52	.2726	181.26	362.5
70	68.4	.2206	187.94	375.9
75	51.76	.167	193.19	386.4

APPENDIX C

CALCULATION OF THE MASS AVERAGED FLOW ANGLE

When the flow is non-uniform at the measurement plane, average values can be defined using the conservation equations. For example, applying conservation of angular momentum between the flow entering through the swirl vanes and the test section inlet:

$$\int_{\dot{m}_1} r_1 V_1 \sin \beta_1 d\dot{m}_1 - \int_{\dot{m}_2} r_2 V_2 \sin \beta_2 d\dot{m}_2 = r_1 \bar{\bar{V}}_{\theta_1} \dot{m}_1 - r_2 \bar{\bar{V}}_{\theta_2} \dot{m}_2$$

$$C(1)$$

where $\bar{\bar{V}}_\theta$ is the mass flow average of the tangential velocity component which is defined as:

$$\bar{\bar{V}}_\theta = \frac{1}{\dot{m}} \int_{\dot{m}} V_\theta d\dot{m} \qquad C(2)$$

Similarly conservation of mass gives:

$$\dot{m} = \int_0^\ell \rho_2 V_2 \cos \beta_2 (2\pi R_2) d\ell_2 = \int_0^\ell \rho_2 (2\pi R_2) V_{R_2} d\ell_2$$

$$= \rho_2 (2\pi R_2) K_{B_2} \bar{\bar{V}}_{R_2} \ell_2 \qquad C(3)$$

where K_{B_2} is defined as the "blockage factor" and relates the area average $(\bar{V}_{R_2})$ and mass average $(\bar{\bar{V}}_{R_2})$ velocity components, thus

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$$K_{B_2} = \bar{V}_{R_2} / \bar{\bar{V}}_{R_2} \qquad\qquad C(4)$$

Consistent with Eq. C(3) and Eq. C(4) the definition of the area-averaged radial component of velocity is:

$$\bar{V}_{R_2} = \frac{1}{\ell_2} \int_0^{\ell_2} V_{R_2} \, d\ell \qquad\qquad C(5)$$

The mass-averaged radial component of velocity is obtained from Eq. E(3), thus

$$\bar{\bar{V}}_{R_2} = \frac{\dot{m}}{\rho_2 (2\pi R_2) K_{B_2} \ell_2} \qquad\qquad C(6)$$

The mass-averaged flow angle ($\bar{\bar{\beta}}_2$) can be defined from:

$$\tan \bar{\bar{\beta}}_2 = \frac{\bar{\bar{V}}_{\theta_2}}{\bar{\bar{V}}_{R_2}} \qquad\qquad C(7)$$

so that

$$\bar{\bar{\beta}}_2 = \tan^{-1}\left(\frac{\bar{\bar{V}}_{\theta_2}}{\bar{\bar{V}}_{R_2}}\right) \qquad\qquad C(8)$$

To obtain the value of $\bar{\bar{\beta}}_2$, from probe survey measurements, and blockage factor to use in the control volume analysis (Appendix D), the following data reduction is required:

1. Calculate the area-averaged radial velocity ($\bar{V}_{R_2}$).

$$\bar{V}_{R_2} = \frac{1}{\ell_2} \int_\ell V_{R_2} d\ell = \frac{1}{\ell_2} \int_\ell V_2 \cos \beta_2 d\ell \qquad C(9)$$

where, if the flow is assumed to be incompressible

$$V_2 = [\frac{(P_1 - P_A)}{\rho/2}]^{.5} \qquad C(10)$$

Substituting Eq. C(10) into C(9):

$$\bar{V}_{R_2} = \frac{1}{\ell_2} (\frac{2}{\rho})^{.5} \int_{\ell_2} (P_1 - P_A)^{.5} \cos \beta_2 d\ell \qquad C(11)$$

where $\beta_2 \equiv \beta_2(\ell)$ is the measured flow angle at the exit of the plywood walls, and $(P_1 - P_A)$ is the difference between the total pressure measured by the 5-hole probe and ambient.

2. Calculate the mass-averaged radial velocity using:

$$\bar{\bar{V}}_{R_2} = \frac{1}{\dot{m}} \int_{\dot{m}} V_{R_2} d\dot{m} = \frac{1}{\bar{V}_{R_2} \ell_2} \int_0^{\ell_2} V_{R_2}^2 d\ell \qquad C(12)$$

3. Calculate the blockage factor using:

$$K_{B_2} = \frac{\bar{V}_{R_2}}{\bar{\bar{V}}_{R_2}} \qquad C(13)$$

4. Calculate the mass-averaged tangential velocity using:

$$\bar{\bar{V}}_{\theta_2} = \frac{1}{\dot{m}} \int_{\dot{m}} V_{\theta_2} d\dot{m} = \frac{1}{\bar{V}_{R_2} \ell_2} \int_0^{\ell_2} V_{\theta_2} V_{R_2} d\ell \qquad C(14)$$

5. Calculate $\bar{\beta}_2$ using Eq. C(8).

APPENDIX D

CONTROL VOLUME ANALYSIS

1. The equation for tan β_2
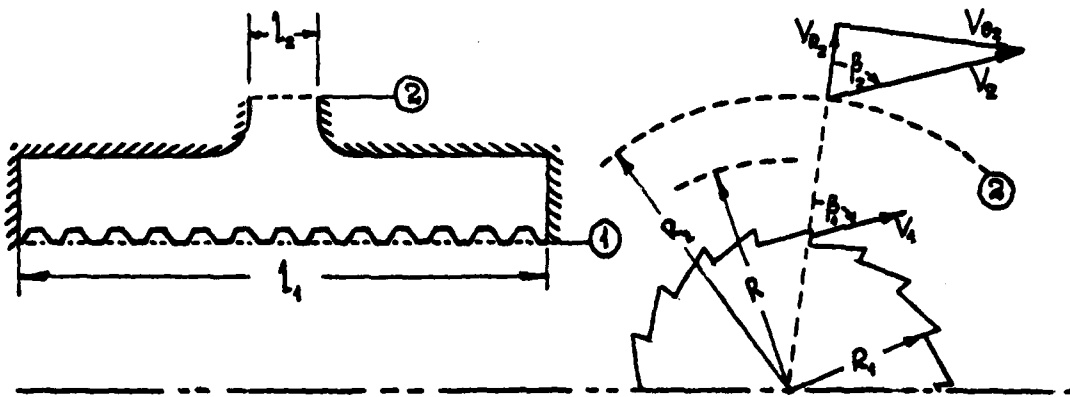
Figure Dl.   Control Volume Analysis Schematic

Assumptions:

1. Constant density $\rho_1 = \rho_2$

2. Radial inlet surface S_1 made up of small nozzles distributed along the GC.

3. The wall surface (IW) consists of:

    a. The outside area of the GC;

    b. The area of the JW faces;

  c. Inside area of outer casing up to the test section inlet.

4. Uniform outlet conditions (Station 2).

5. Zero axial velocity (V_z) at Stations 1 and 2.

Following Reference 6, the axial moment exerted by the air on the walls of the control volume (Fig. D1) is given by:

$$M_{aw} = \int_{S_1} \bar{R}_1 V_1 \sin \beta_1 d\dot{m}_1 - \int_{S_2} R_2 V_2 \sin \beta_2 d\dot{m}_2$$

$$+ \int_{S_1} \vec{R}_1 \times d\vec{F}_1 + \int_{S_2} \vec{R}_2 \times d\vec{F}_2 \qquad \text{D(1)}$$

The force on a surface element can be written in terms of its components normal to and in the surface as:

$$d\vec{F} = -p\hat{n}dS - \tau\hat{t}dS \qquad \text{D(2)}$$

so that

$$\int_{S_1} \vec{R}_1 \times d\vec{F}_1 = \int_{S_1} \vec{R}_1 \times (p_1 \hat{n}dS)$$

$$= \bar{R}_1 p_1 A_1 N \ell_1 Z \qquad \text{D(3)}$$

From continuity

$$\dot{m} = \int_{S_1} d\dot{m}_1 = \int_{S_2} d\dot{m}_2 \qquad \text{D(4)}$$

so that

$$\int_{S_1} d\dot{m}_1 = \rho_1 V_1 \sin \beta_1 \, k_{B_1} A_1 ZN\ell_1 \qquad \text{D(4.1)}$$

and

$$\int_{S_2} d\dot{m}_2 = \rho_2 V_2 \cos \beta_2 \, k_{B_2} (2\pi R_2)\ell_2 \qquad \text{D(4.2)}$$

Substituting Eq. D(3), D(4.1) and D(4.2) into D(1):

$$M_{aw} = \rho_1 \bar{R}_1 V_1^2 \sin^2 \beta_1 \, kB_1 A_1 ZN\ell_1 + \bar{R}_1 p_1 A_1 ZN\ell_1$$

$$- \rho_2 R_2 V_2^2 \sin \beta_2 \cos \beta_2 \, kB_2 (2\pi R_2)\ell_2 \qquad \text{D(5)}$$

The different terms in the LHS of Equation D(5), can be written in terms of the moments of the normal and tangential stress components given in Equation D(2). The only contributions to the axial moment, comes from shear stress components (τ) on the cylindrical walls, and normal stress components (p_w) on the non cylindrical surfaces of the swirl vanes. Thus:

$$M_{aw} = \int_{IW} \tau \, R \, dS + \int_a^b p_w R \sin \theta \, dS' \qquad \text{D(6)}$$
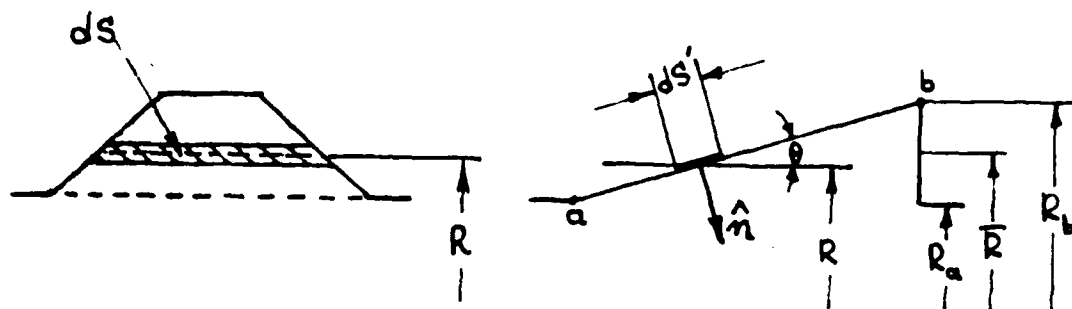
Figure D2. Stress Components on the Swirl Vanes

From Figure D2,

$$dS = dS' \sin \theta \qquad\qquad D(7)$$

so that

$$M_{aw} = \int_{IW} \tau \, R \, dS + ZN\ell_1 \int_a^b p_w R dS \qquad D(8)$$

Combining Equations D(5) and D(8)

$$\int_{IW} \tau R dS + ZN\ell_1 \int_a^b (p_w - p_1) R dS = \dot{m}(\bar{R}_1 V_1 \sin \beta_1 - R_2 V_2 \sin \beta_2)$$

$$D(9)$$

Solving Equation D(9) for $\sin \beta_2$, dividing both sides by $\cos \beta_2$, and substituting V_1 and V_2 from Equations D(4.1) and D(4.1), we obtain:

$$\tan \beta_2 = \frac{\overline{R}_1}{R_2} \times \left[\frac{K_{B_2}(2\pi R_2)}{K_{B_1} A_{SV}} \right] \times \left\{ \frac{\ell_2}{\ell_1} \right\} \times \{1 - C_p - C_\tau\} \qquad D(10)$$

where, the pressure term

$$C_p = \frac{ZN\ell_1}{\dot{m}V_1 \sin \beta_1} \int_a^b (p_w - p_1) \frac{R}{R_1} dS \qquad D(11)$$

and the friction term

$$C_\tau = \frac{1}{\dot{m}V_1 \sin \beta_1} \int_{IW} \tau \frac{R}{R_1} dS \qquad D(12)$$

The design analysis in Appendix A is the special case of $C_p = C_\tau = 0$. The values of C_p and C_τ can be obtained using various assumptions.

2. Calculation of the Pressure Term

Writing,

$$\int_a^b \frac{R}{R_1} dS \cong A_{SV} k_{B_1}$$

and $(p_w - p_1) \neq f(R)$, then

$$C_p \cong \frac{ZN\ell_1 A_{SV} K_{B_1}}{\dot{m}V_1 \sin \beta_1} (p_w - p_1) \qquad D(13)$$

where $(p_w - p_1)$ has a maximum value of $(p_{t_1} - p_1)$, or more realistically, $(p'_{t_1} - p_1)$, where p'_{t_1} is the stagnation pressure after jet mixing.

In order to calculate p'_{t1}, a sudden expansion is assumed downstream the swirl vanes. The following formula, derived in Reference 4, results from mixing at constant pressure:

$$\frac{p_w - p_1}{\frac{1}{2}\rho_1 V_1^2} = 2\,\frac{A_1}{A_{MIX}}\left(1 - \frac{A_1}{A_{MIX}}\right) \qquad\qquad D(14)$$

where A_{MIX} is the area of the flow when total mixing has occurred and the velocity is uniform.

From experimental measurements (Fig. D3), it was estimated that total mixing occurs within .3" from the GC surface, so as shown in Fig. D4 the area ratio is given by:

$$A_1/A_{MIX} = .3916$$

hence Equation D(14) becomes

$$p_w - p_1 = \frac{1}{2}\rho V_1^2 \times (.4765) \qquad\qquad D(15)$$

Substituting to Equation D(13), the pressure term becomes:

$$C_p = \frac{(.23875)}{\sin^2\beta_1} \qquad\qquad D(16)$$

It is noted that the pressure term changes the value of $\tan\beta_2$ by nearly 25%.
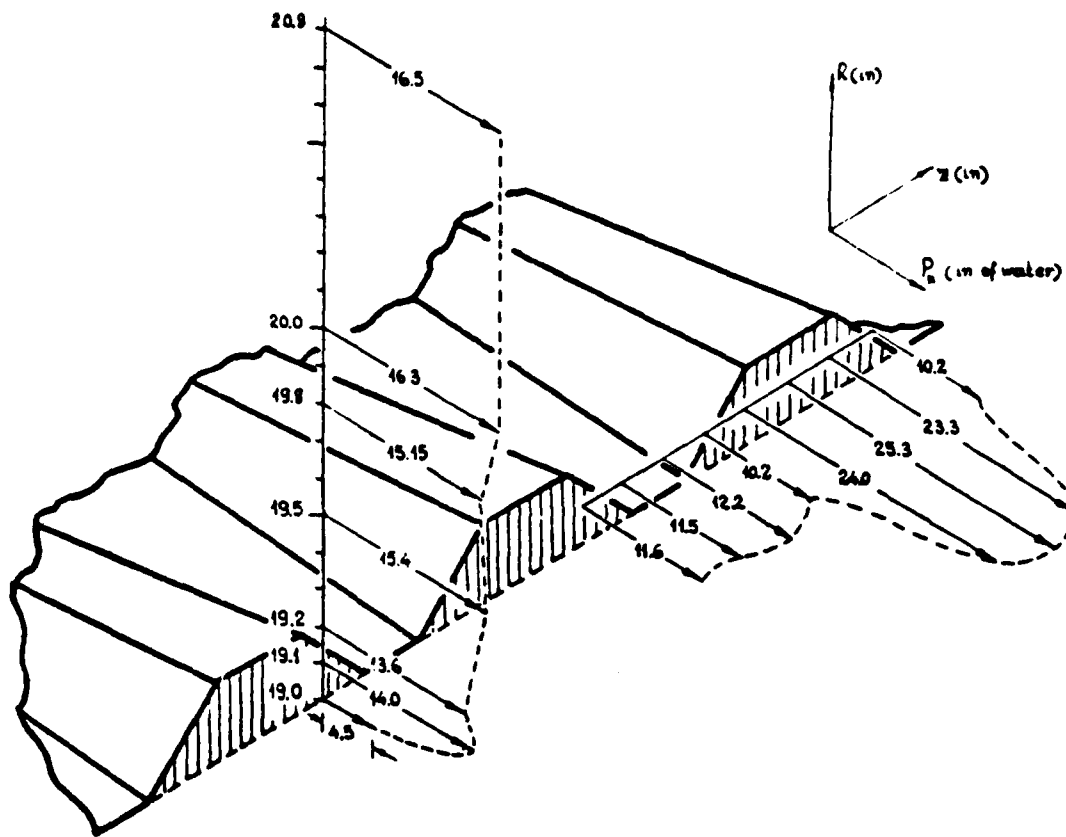
Figure D3.   Total Pressure Distribution in the Flow
Generator and Near the Surface of the
Generating Cylinder Measured with a Kiel Probe
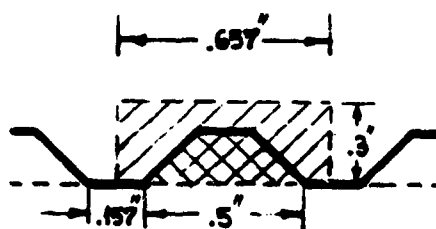
Figure D4. A_1/A_{MIX} Area Ratio Schematic

3. Calculation of the Friction Term

The friction term is approximated using an average velocity ($\overline{V}_{IW}$) for the flow over the inner walls of the CDTD; the tangential stress is given by:

$$\tau = \frac{1}{2} C_F \, \rho \, \overline{V}_{IW}^2 \qquad\qquad D(17)$$

and values are required for $\overline{V}_{IW}$ and C_F.

a. Calculation of $\overline{V}_{IW}$

In terms of Kiel probe measurements,

$$V_1 = \left[\frac{P_K - P_A}{\rho/2}(5.202)\right]^{.5} \qquad\qquad D(18)$$

From Fig. D3 and using Eq. D(18) with the pressure differences ($p_K - p_A$) from measurements and $\rho = .002766$ <slugs/FT^3>, the following Table D1 is obtained, for the velocity profile close to the surface of the GC.

Define the blockage factor for one jet as:

$$K_{B_1} = \frac{\displaystyle\int_5^9 V_1(z)\,dz}{(z_9 - z_5)V_{1_{MAX}}} = .841 \qquad\qquad D(19)$$

where the average inlet velocity is given by

$$\overline{V}_1 = V_{1_{MAX}} \times K_{B_1} = 183.45 \text{ ft/sec} \qquad\qquad D(20)$$

TABLE D1

VELOCITY PROFILE CALCULATION AT THE
SURFACE OF THE GENERATING CYLINDER

Point #	$2(p_K - p_A)$ (in H_2O)	V_1 (FPS)
1	14.0	162.0
2	11.6	147.7
3	11.5	147.06
4	12.2	151.5
5	10.2	138.5
6	24.0	212.45
7	25.3	218.13
8	23.3	209.33
9	10.2	138.5

The velocity over the outer casing walls (V_{ow}) can be approximated from the pressure difference to atmosphere measured at R = 20.8" (Fig. D4), then

$$V_{ow} = [\frac{\Delta P \ (R = 20.8")}{\rho/2}(5.202)]^{.5} = 176.16 \ \text{FPS} \qquad D(21)$$

From Equations D(20) and D(21) the average velocity over the inner walls ($\overline{V}_{IW}$) can be estimated:

$$\overline{V}_{IW} = \frac{\overline{V}_1 + V_{ow}}{2} = 179.8 \ \text{FPS} \qquad D(22)$$

b. Calculation of C_F

The hydraulic diameter [Ref. 5] is used to calculate the Reynolds number. The Reynolds number is given by:

$$Re = \frac{d_h \bar{V}_{IW}}{\nu} \qquad \text{D(23)}$$

where

$$d_h = \frac{4A}{C} \qquad \text{D(24)}$$

and A denotes the cross-sectional area and C the wetted perimeter.

For the CDTD

$$A = 2\ell_1 + 4\ell_2 \equiv .41 \text{ FT}^2$$

$$C = 2\ell_1 + 12 \equiv 5.0625 \text{ FT}$$

hence

$$d_h = .324 \text{ FT} \qquad \text{D(24.1)}$$

For $\nu = 1.57 \times 10^{-4} \text{ FT}^2/\text{sec}$, Eq. D(23) gives:

$$Re = 3.63 \times 10^5 \qquad \text{D(25)}$$

From Prandtl's universal law of friction for turbulent
flows through pipes [Ref. 5]:

$$C_F = 3.59 \times 10^{-3} \qquad\qquad D(26)$$

Substituting all specified terms into Eq. D(12):

$$C_\tau = \frac{1.795 \times 10^{-3}}{\sin^2\beta_1} \times \left(\frac{A_{IW}}{A_{T1}}\right)\left(\frac{\overline{V}_{IW}}{\overline{V}_1}\right)^2 \qquad\qquad D(27)$$

4. Calculation of Outlet Angle

Using Eq. D(16) and Eq. D(27) in Eq. D(10),

$$\tan\beta_2 = \frac{\overline{R}_1}{R_2} \times \left(\frac{A_{T2}}{A_{T1}}\right)\left[1 - \frac{.23875}{\sin^2\beta_1} - \frac{1.795 \times 10^{-3}}{\sin^2\beta_1}\left(\frac{\overline{V}_{IW}}{\overline{V}_1}\right)^2\left(\frac{A_{IW}}{A_{T1}}\right)\right]$$

$$D(28)$$

For the values:

$$\overline{R}_1 = 19.1 \text{ in}$$

$$R_2 = 25 \text{ in}$$

$$\ell_2 = 2.62 \text{ in}$$

$$A_{T1} = A_{SV}ZN\ell_1 k_{B_1} = 5.045\ell_1 \text{ in}$$

$$k_{B_2} (\ell_1 = 24.375) = .925 \text{ (average measured)}$$

$$k_{B_2} (\ell_1 = 8.0) = .83 \text{ (average measured)}$$

$$A_{T2} = 2\pi R_2 \ell_2 k_{B_2} = 411.55 \, k_{B_2} \, in^2$$

$$A_{IW} \doteq 2\pi \bar{R}_1 \ell_1 + 2\pi R_{OC}(\ell_1 - \ell_2) + 2\pi(R_{OC}^2 - R_1^2) + 2\pi(R_2^2 - R_{OC}^2)$$

$$= 7454 \, in^2$$

$$\beta_1 = 84°$$

Substituting these values into Eq. D(28), the flow angle as a function of the exposed length (ℓ_1) of the generating cylinder (since k_{B_2} is also a function of ℓ_1) is given by:

$$\beta_2 = \tan^{-1}\left[(40.78)\left\{\frac{k_{B_2}}{\ell_1}\right\}\right] \qquad D(29)$$

From Eq. D(29), for $\ell_1 = 24.375''$ and $k_{B_2} = .925$:

$$\beta_2 \, (\ell_1 = 24.375) = 57.13°$$

Also, for $\ell_1 = 8.0$ in and $k_{B_2} = .83$; Eq. D(29) gives:

$$\beta_2 \, (\ell_1 = 8.0) = 76.7° .$$

MERIDL INPUT FILES

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                                             **********************
                                             *       NEMIOL       *
                                             *   PROGRAM INPUT    *
                                             **********************

CUTO  IS USING MODEL (L2 = 1.305 IN)  R2 = 75.    6/9/83

  GENERAL   INPUT   DATA
     GAM            AR              MSFL          OMEGA          REDFAC         VELTOL         FNEW          ONEW
   1.400000       1716.000       .1600000        .0            1.000000      .1000000E-01   .5000000      .5000000
     VELTOL   HAS   BEEN   REDUCED   BY   THE   MINIMUM   OF   FNEW   OR   ONEW   TO   =      VELTOL
                                                                                            .4999999E-02
     MBI    NBC    NM .   NMT    NBL    NHUB   NTIP    NIN    NOUT    NBLPL   NPPP   NOSTAT   NSL    NLOSS
      0      0      30     10     1      11     15      9      6       0       0      0       22      0
    LSFR   LTFL   LPRNT  LOUT   LBLAD  LBEAN
     1      1      0      1      0      0
    ANGOUT
   45.00000

  HUB   AND   SHROUD   INPUT   DATA
    ZLPIN            ZLPBI            ZOMBC            ZOMOUT           ROMIN            ROMBI            ROMBO            ROMOUT
  .5000000           .0               .0             2.025400         1.416700          .0               .0             2.474600
    ZHUB   ARRAY
  .5000000         .7500000         1.000000         1.250000         1.500000         1.750000         1.858700         1.942100
  2.000000         2.025400         2.025400         2.025400         2.025400
    RHUB   ARRAY
  1.416670         1.416670         1.416670         1.416670         1.416670         1.416670         1.416670         1.439000
  1.500000         1.583300         1.750000         2.000000         2.474600
    ZTIP   ARRAY
  .5000000         .7500000         1.000000         1.250000         1.500000         1.750000         1.791700         1.833300
  1.875000         1.891700         1.908200         1.908300         1.916700         1.916700         1.916700
    RTIP   ARRAY
  1.750000         1.750000         1.7500           1.750000         1.750000         1.750000         1.755600         1.775400
  1.822500         1.853800         1.8875           1.906250         2.000000         2.250000         2.500000

  UPSTREAM   INPUT   DATA
    ZFIN             ZTIN             RHIN            RTIN
  .5000000         .5000000         1.416670         1.750000
    RADIN   ARRAY
  1.416670         1.458340         1.500000         1.541670         1.583340         1.625000         1.666670         1.708330
  1.750000
    TIN   ARRAY
  520.0000         520.0000         520.0000         520.0000         520.0000         520.0000         520.0000         520.0000
  520.0000
    PTIN   ARRAY
  2116.000         2116.000         2116.000         2116.000         2116.000         2116.000         2116.000         2116.000
  2116.000
    ENTIN   ARRAY
  386.3701         386.3701         386.3701         386.3701         386.3701         386.3701         386.3701         386.3701
  386.3701

  DOWNSTREAM   INPUT   DATA
    ZFOUT            ZTOUT            RHOUT            RTOUT
  2.025400         1.916670         2.474600         2.583300
    RADOUT   ARRAY
  2.474600         2.500000         2.520800         2.541700         2.562500         2.583330
    LOSOUT   ARRAY
  .9999999E-03     .9999999E-03     .9999999E-03     .9999999E-03     .9999999E-03     .9999999E-03

  OUTPUT   STREAMLINE   FLOW   FRACTION   DATA
    FLFN   ARRAY
  .0               .5000000E-01     .1000000         .1500000         .2000000         .2500000         .3000000         .3500000
  .4000000         .4500000         .4750000         .5000000         .5500000         .6000000         .6500000         .7000000
  .7500000         .8000000         .8500000         .9000000         .9500000         1.000000
```

MERIDL OUTPUT FILES

END
DATE
FILMED
2-84
DTIC

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

** STREAMLINE NUMBER 21 — STREAM FUNCTION = 0.9500 **

** STREAMLINE NUMBER 22 — STREAM FUNCTION = 1.0000 **

••• STREAM FUNCTION, INTERIOR VELOCITIES, VELOCITY COMPONENTS, ANGLES, AND SURFACE VELOCITIES •••

ALONG STREAMLINES

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•••••••••••••••••
• FULL  MASSFLOW  •
• ••••••••••••••• •
• ITERATION NO. 2 •
•••••••••••••••••
```

•• STREAMLINE NUMBER 1 — STREAM FUNCTION = 0.0 ••

•• STREAMLINE NUMBER 2 — STREAM FUNCTION = 0.0503 ••

LIST OF REFERENCES

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